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Safety, Durability and Reliability of Metal Structures

Sécurité, durabilité et fiabilité des constructions métalliques

Sicherheit, Dauerhaftigkeit und Zuverlässigkeit von Metallkonstruktionen

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1. General Aspects.

The design of safe, durable and maintainable engineering structures requires the development of a general methodology as well as of specific procedures for

a) the verification of their functional and structural integrity (serviceability and safety);
b) the prediction of their expected service life under anticipated operational conditions (durability);
c) the assessment of the risk associated with such verification and predictions (reliability).

Such procedures must necessarily be integrated to involve all phases, from the planning phase of materials evaluation and selection to the final phase of reliability demonstration and the setting-up of an inspection and maintenance program. It is the lack of recognition of the necessity for integration of all phases as well as of the complexity of the interactions between inherent material properties, selected design criteria, structural details, manufacturing processes and conditions of operation that has been responsible for some of the most costly errors in materials selection and design that have been committed. Materials evaluation for the purpose of assurance of superior structural integrity and reliability is not identical with conventional evaluation of inherent material properties, but involves the comparative study of alternative systems and process technologies in which all interactions are considered and from which the basic parameters for the subsequent integrity-, durability- and risk analysis can be deduced.

The significance of any of the above aspects will vary with the type of structure, its expected operational utility and usage and the material and fabrication process used in its construction. Thus for instance the fact that the surveillance procedure for riveted railroad bridges consists exclusively of periodic visual and (possibly) sonic in-service inspections of the rivets and gusset plates in the principal connections, while the surveillance procedure for long-range aircraft involves several extensive out-of-service inspections of the complete load-carrying structure reflects the differences in structural type, operational usage and material of construction rather than a basic difference in the general reliability outlook of a particular industry. The contention that "problems of structural safety and reliability are viewed in different terms in different branches of engineering" (Introductory Report, p. 9) would be valid only if it were meant to imply that the degree of acceptance of a rational approach to problems of safety and reliability is not uniform in the various branches of engineering. Unfortunately, this acceptance is, at present, still rather low in all branches of engineering concerned with mechanical and structural design (as distinct from the design of electronic systems); the apparent differences in approach are nothing else but a reflection of the differences in the assessment of the relative significance of the above three aspects of structural analysis and design.

The Introductory Report attempts to deal with the problem of design for repeated loading in terms of the first aspect (integrity) by restating as "Generalized Formulation" the by now widely accepted probabilistic concept of safety under the single application of a critical load or load combination.[1] The conclusion is obvious that "in these general terms the problem (safety for repeated loading) apparently has no practical solution" (Introductory Report, p. 10).

Attempts have been made to extend the simple probabilistic ultimate load safety concept to design for repeated loads producing fatigue damage by a method [2] that resembles the somewhat vague concept suggested in Section 3.5 but permits the introduction of modern more recent procedures of fracture mechanics for the purpose of fatigue life prediction and of order statistical concepts for risk assessment.[3].

2. Fracture Mechanics Model.

This method is based on the combination of the equation for the unstable crack-propagation stress intensity $K_c=F.\sigma_u\sqrt{c_u}$ determining the gross ultimate load stress σ_u for a structural part with crack extension under the (repeated) stress intensity range $\Delta K=F.(\Delta\sigma)\sqrt{c}$, of the form $(dc/dN)=M(\Delta K)^r$, where F, M and r are constants that depend on geometry and material. Integration of the crack-extension equation over N stress-intensity cycles with initial defect c_i produces an expression for the gross stress σ_R at ultimate failure of the damaged structural part that has been subject to $N<N_F$ stress intensity cycles (residual strength) where $N_F \sim (K_c/K_i)^{r-2}$ denotes the number of cycles at which the initial defect c_i attains the critical value c_u (ultimate strength):

$$\sigma_R \sim \mathrm{Const.}\sigma_u[1-\frac{N}{N_F}]^{\frac{1}{r-2}}$$

Unfortunately this simple method is applicable only to monolithic single-load path structures containing severe (pre-existing) material or manufacturing defects (cracks, inclusions, welds) in which fatigue failure arises as the terminal condition of slow crack extension from a pre-existing defect, a condition to be avoided in any good design. Even in this case, however, the estimate of N,

N_F or σ_R is subject to considerable statistical uncertainty because of significant scatter of observed crack propagation rates, critical crack-size and other relevant parameters. The scatter range for the same structural metal of the crack-propagation rates alone is between 1:5 and 1:10, and combines with the uncertainties involved in the assessment of the severity of pre-existing defects and in the specification of the operational loading spectra. Only in the case of essentially non-statistical operational loading (railroad bridges, pressure vessels) is it at all possible to rely on the existence of an "endurance limit" of a metal like steel and to disregard fatigue in the design of structural members by keeping the maximum stress amplitude below the "endurance limit".

Even if fracture mechanics analysis is only used for the determination of appropriate inspection intervals by considering the slow propagation of the largest undetectable crack to critical size, the inherent uncertainties of recorded crack-propagation rates at constant stress range intensities, as well as the additional uncertainties arising from attempts at superposition of such rates at variable stress range intensities, in view of the severe interactions between high and low intensities mainly due to residual stress fields at the crack-roots, preclude a better than order-of-magnitude prediction of "safe" inspection intervals; such interaction may also severely reduce or destroy the "limiting levels" of stress-intensity below which crack-propagation is non-existent. Nevertheless, the knowledge of crack-propagation rates for structural metals under conditions representative of the structure and of its operation is basic in the analysis of fatigue behavior and adequate material selection.

In the case of a redundant, multiple-load-path "damage-tolerant" structure with or without pre-existing defects this oversimplified model of the fatigue process bears no resemblance to reality and is therefore inapplicable. It completely disregards the stage of fatigue-crack initiation which, contrary to the assumption made in the fracture mechanics interpretation of fatigue, makes up a significant portion of the fatigue life, even in well-designed monolithic structures in the production of which a sufficiently high level of quality control has been imposed.

3. Fatigue Life Prediction.

The lack of confidence in analytical procedures of fatigue life prediction arises from the fact that, so far, no analytical rule of fatigue damage accumulation applied to variable stress-amplitudes and variable mean stress produces life predictions that consistently agree with life test results more closely than one order of magnitude. This is not only the result of statistical uncertainty, but of the impossibility to combine all physical aspects of fatigue damage accumulation in a structure with redundancies and complex interactions subject to a complex, neither purely stochastic nor purely deterministic load sequence, into an analytical damage accumulation rule that would reflect the trend of damage accumulation as well as the statistical uncertainties involved. The widely used linear damage accumulation rule, with simple modifications to account for "interaction" and "residual stress" effects [4] has the advantage of maximum simplicity. Identification of the loading conditions producing the major portion of the fatigue damage, for instance the ground-air-ground cycle in the transport airplanes, and isolated study of the damage accumulation under such conditions alone might produce a more reliable analytical procedure of fatigue life estimation by concentrating on the dominant damage mechanism. Even in this case, however, the analytically predicted life will represent not more than an order-of-magnitude approximation, always to be verified by full scale tests.

The fatigue performance of a structure is significantly affected but not decisively determined by the fatigue performance of the material under conditions of laboratory tests. It has been estimated that more than 90 percent of fatigue failures in structures and machine parts are primarily due to faulty design of details or to production defects; many of these failures could therefore be avoided by increased attention to design and design details, and by stricter control of production processes, without improving the fatigue performance of the material itself. On the other hand, it is unlikely that serious effects of faulty design or of inadequate surface treatment can be fully compensated by the selection of an alloy of better fatigue performance in laboratory tests.

The character of fatigue failures in various types of structures and structural parts depends on the relative significance of the different factors by which their fatigue performance is affected. Thus fatigue in axles, shafts, pins, etc. under relatively steady operating conditions, as in motors, machinery, ships and railroad equipment is dominated by the stress-concentrations associated with characteristic design-features, such as fillets, section-changes, key-ways, holes, corners, etc. As diameters increase, inhomogeneities in the metal and residual stresses arising in the forming process (cooling gradients, metallurgical transformations) become increasingly important. Fatigue in riveted structures is dominated by stress-concentrations and fretting in the connections; for structures under highly variable loading, it is significantly affected by the plastic redistribution of stresses under high load-amplitudes. Fatigue under acoustic noise is affected by the character of the noise spectrum as well as by panel geometry, by the damping of the excited modes of the structure and the intensity of the noise itself. Thus it is known that the same noise level applied to the same structure produces different fatigue lives depending on whether the energy is concentrated in a single frequency (siren noise) or distributed over a multidude of frequencies (jet-noise). Fatigue in welded structures is dominated by metallurgical changes in the weld-affected zone combined with excessive rigidity of and residual thermal stresses in the connections. Fatigue of parts or structures repaired or built-up by welding is invariably caused by the combined metallurgical, thermal and mechanical effects associated with the welding. Fatigue of complex structures under variable operating conditions, such as airframes or high-temperature service equipment, can usually not be attributed to a dominant cause, unless failure is clearly due to faulty design of details.

It is to be expected that the smaller the number of contributing factors and the better they can be controlled, the easier is design information obtainable from specimen fatigue tests, and the more reliable the design for fatigue and the prediction of fatigue life on the basis of this information. The more the fatigue performance depends on a combination of several factors, the more difficult the separate assessment of the effects of the individual factors. The more important therefore the full-scale fatigue test of the structure for the double purpose of eliminating the weakest spots by observation of the actual sequence of localized failures, and of predicting the order of magnitude of the fatigue life of the structure in which these spots have been adequately strengthened. Accelerated fatigue tests, at constant high stress amplitude, in which the sequence and character of the service failures is not duplicated and a different type of failure is produced, are useful only as means of locating points of excessive initial damage; they do not provide information for the estimate of operational life.

4. Aspects of Fatigue Design.

The dependence of fatigue failure in structures on a combination of factors the effect of each of which can only be specified with a certain margin of uncertainty makes it unrealistic to attempt to predict the fatigue life of a structure even under rather closely defined operational condition in any but a statistical manner. Fatigue design of structures is therefore a problem of "reliability"-analysis rather than of stress- or strength-analysis. Fatigue design differs significantly from ultimate-load design by the complexity and resulting vagueness of the correlation of load, stress and carrying capacity. The large number of contributing factors, the combined effects of which determine the fatigue life of a structure, necessarily produce a rather wide scatter in the fatigue life even of nominally identical structures under nominally identical operating conditions.

The approach to fatigue design of structural parts and structures must be determined by their "fatigue-sensitivity", defined as a measure, at a specified service life, of the probability of the structure to fail in fatigue rather than under a single application of the "ultimate" load.[5] As this probability will depend, among other, on operating conditions and the expected service life, the "fatigue-sensitivity" of a structure cannot be specified independently of such conditions; the same structure may be "fatigue-insensitive" under one set of conditions and "fatigue-sensitive" under another. Under conditions of low fatigue-sensitivity it will be usually unnecessary to design for a specific operational life in fatigue; fatigue design may be simply limited to elimination, by constructive means, of the most obvious sources of crack initiation, so as to avoid a possible reduction of the expected fatigue life to within range of the expected life with respect to the ultimate load. Specific design for fatigue, supplemented by extensive fatigue testing is necessary only for medium and high "fatigue-sensitivity" for which fatigue failure is the expected type of failure; tests of full scale structures are an integral part of fatigue design. The prediction of the expected operational life of the structure and the prevention of catostrophic consequences of possible failure within this period (which cannot be excluded because of the irreducible uncertainty of such prediction) is the dual purpose of such design.

Fatigue design for finite life as a problem of "reliability" must be concerned with a rational measure of reliability; an expedient measure is provided by the probability of failure-free operation during the specified service life L. Statistically this is the probability of survival as a function of service life, the survivorship-function, which is thus identical with the "reliability function" R(L). It is the advantage of this statistical measure of reliability that it permits the quantitative correlation, under simplifying assumptions, of the reliability of the structure with the reliability of its components, as well as of the reliability under fatigue conditions with the reliability under ultimate load conditions. The introduction of a quantitative measure or scale of "fatigue sensitivity" and a classification of structures or structural designs in terms of such a measure makes it possible to utilize the existing results of full-scale fatigue tests in the fatigue analysis of newly designed structures, by concentrating in this analysis on those factors by which the fatigue sensitivity of the new structure is expected to differ from that of previously designed structures of specified fatigue sensitivity, for which both testing and operating experience has been accumulated.

The procedures of reliability analysis of structures under fatigue conditions are based on the concept of "risk" of failure after N load applications, r(N), in terms of which a quantititive measure of "fatigue sensitivity can be defined. Since failure of a structure or part can be caused either by chance coincidence of an extremely rare "ultimate load" with an initial resistance sufficiently low to produce instantaneous collapse, or by fatigue under repeated load-intensities significantly lower than the ultimate load, and represented by a spectrum of operational loads, a reasonable measure of fatigue sensitivity is the ratio of the risk of fatigue failure to that of "ultimate load" failure at any load application. This ratio

$$f(N) = \frac{r_F(N)}{r_u(N)}$$

where r_F denotes the risk of fatigue failure, r_u that of "ultimate load" failure, can therefore be designated as a "coefficient of fatigue sensitivity" of the structure at a certain "age" N; since $r_F(N)$ may be assumed to increase with age by definition of the phenomenon of "fatigue", the fatigue sensitivity of a structure will also tend to increase with age. The larger f(N), the larger the probability, at any value of N, that the structure will fail in fatigue rather than by ultimate load collapse. If $N=N^*$ denotes the expected operational life of the structure, the value $f(N^*)=f^*$ characterizes the fatigue sensitivity of the structure at the end of this life rather than at any "age" N, and is therefore an important design parameter:

It is tentatively assumed that a rational classification of the fatigue sensitivity of systems or structures might be based on the following scale.

(I)	$0 < f^* < 0.1$	fatigue insensitive structures
(II)	$0.1 < f^* < 1.0$	moderately fatigue sensitive structures
(III)	$1.0 < f^* < 10$	highly fatigue sensitive structures
(IV)	$10 < f^*$	fatigue critical structures

Class (I) structures need be designed for ultimate load only; Class (II) structures should be designed for ultimate load, but with careful consideration of details with respect to fatigue performance; only the critical components and connections are fatigue-tested by accelerated procedures to eliminate fatigue-prone details. Class (III) structures should be both designed and tested for fatigue, with at least one full-scale fatigue test under a representative load spectrum, in addition to component and connection fatigue tests sufficient to estimate their usable minimum operational life. Class (IV) structures or parts, if they cannot be avoided, should be designed for fatigue alone and used only if a sufficient number of replications of full-scale fatigue test can be performed to permit a reliable statistical estimate of mean or median fatigue life and of the scatter range. However, important structures, the failure of which would have serious consequences, should be designed so as not to fall into Class (IV). This may be done either by reducing the risk of fatigue failure or by limiting the operational life, or by imposing stringent procedures of inspection for fatigue cracks, the discovery and repair of which would make the maximum inspection period the "critical" operational life, to be used in evaluating the fatigue sensitivity.

In terms of the approach to the various aspects of design structures under repeated loading outlined above and believed to reflect the objective conditions of the problem, some of the concepts with which the Introductory Report seems to be concerned are either outdated (section 3.2), of dubious validity (Section 3.3, in particular Eq. 12) or confusing if not misleading (Section 4.1) in the lack of recognition that design for "limit states" (critical loading conditions) and design for repeated loading are different but complimentary aspects of design.

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SUMMARY

The Introductory Report deals with the problem of design for repeated loading on the basis of a generalization of the probabilistic concept of safety under a single load application. The short-comings of this approach are discussed and the basic differences between design for a single limit state and design for fatigue are outlined. The concept of "fatigue sensitivity" of a structure is introduced as a key to the selection of a rational design procedure.

RESUME

Le rapport introductif traîte le problème du dimensionnement en cas de charges répétées sur la base d'une généralisation du concepte probabiliste de sécurité pour une seule application de la charge. Les imperfections de cette méthode sont discutées et les différences fondamentales entre le dimensionnement pour un état limite simple et le dimensionnement à la fatigue sont soulignées. Le concept de "sensibilité à la fatigue" d'une structure est introduit comme point de repère pour le choix d'une méthode de dimensionnement rationnelle.

ZUSAMMENFASSUNG

Der einführende Teil befasst sich mit dem Problem der Bemessung für wiederholte Belastung aufgrund einer Verallgemeinerung des wahrscheinlichkeitstheoretischen Sicherheitskonzepts unter einer einzigen Lastaufbringung. Die Vereinfachungen dieser Näherung werden diskutiert und die grundlegenden Unterschiede zwischen Bemessung auf einen einzigen Grenzzustand und Bemessung auf Ermüdung hervorgehoben. Als Schlüssel zur Auswahl vernünftiger Bemessungsmethoden wird der Begriff der "Ermüdungs-Empfindlichkeit" eines Tragwerks eingeführt.