Columbia University
in the City of New York

DEPARTMENT OF CIVIL ENGINEERING
AND ENGINEERING MECHANICS

INSTITUTE FOR THE STUDY OF FATIGUE AND RELIABILITY

FATIGUE MECHANISMS; FATIGUE PERFORMANCE AND STRUCTURAL INTEGRITY

by

A. M. Freudenthal

FINAL REPORT

March 1963 - September 1969

Sponsoring Agencies
Office of Naval Research
Air Force Materials Laboratory
Advanced Research Projects Agency

Contract No. NONR 266(91)
Project No. NR 064-470

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1. Introduction*

The interdisciplinary approach to fatigue involves research efforts at different levels of "observational resolution". Their correlation is one of the most vexing problems, because what is needed before a correlation of the physical phenomena at the different levels can be attempted, is a correlation of the "semantics" of the observers arising from the differences in their professional background and training. Although such differences are only differences in emphasis, they cannot fail to produce the idiosyncrasies that make communication, that has to precede any attempts at correlation, rather difficult.

In order to establish the unity of purpose in this interdisciplinary research and development effort in fatigue and fracture of structures and materials, it is necessary to correlate its specific objectives in the light of its over-all purpose. Since the individual objectives are pursued by research at different levels of "observational resolution", the correlation of objectives will provide the correlation between those levels, so that the designer or stress-analyst viewing the real structure as a progressively cracking elastic structure, can be made to understand on the one hand the approach of the metallurgist who is attempting to control the initiation and propagation of the crack in the microstructure

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*This Introduction has been prepared as the Opening Paper of the Air Force Conference on Fatigue and Fracture, Miami, December, 1969.

of the metal, and on the other that of the reliability statistician for whom the individual structure in a population or in a fleet is nothing more than a member of a statistical population defined by the distribution function of the time to failure or to a specified "damage". At all three levels the principal concern is with progressive damage in the form of structural defects, with its rate or probability of growth and with the possibilities of its control by material selection and/or by design.

The problem of fatigue and of structural reliability under conditions leading to fatigue has grown in importance with increasing severity of operating conditions, demands for longer operational life and increasing use of high-strength and high-temperature structural materials in the design and construction of modern structures. The problem is equally significant for modern aircraft structures (F111, C5A, VTOL, SST), space structures, particularly the space shuttle, ship structures and deep submergence vehicles, bridges, structures for transport vehicles on land, and many other structures for industrial and defense use.

A huge amount of constant-amplitude fatigue test data has been collected over many years; their relevance to fatigue design is, however, rather obscure. Intensive studies of the physical mechanism of the fatigue phenomenon in metals have been carried out in various laboratories around the world and are continuing. These studies, while of basic importance, are of limited relevance to fatigue design; they necessarily deal with relatively simple metals, such as pure copper, aluminum, or simple binary alloys such as brass for which metal-physical interpretation of the observed phenomena is possible. Very little is known about fatigue in the important very high strength alloys. Numerous theories of fatigue have been proposed and discarded over the years; at present several contradicting theories based on solid state physics concepts are under discussion; however, the relatively wide scatter of the results of fatigue tests coupled with the "order of magnitude" predictions characteristics of solid-state theories has, so far, prevented the formulation of criteria for the effective comparison of theory and experiment. The amount of useless experimentation and testing in the field of fatigue probably exceeds that in almost any other field of engineering research, while the results accomplished are in no relation to the amount of time and funds expended.

The problem of fatigue arose almost immediately with the use of metals in structures subject to dynamic loading, beginning with the introduction of coach service on the roads of France, and continuing with the development of railroad bridges and locomotive axles in England about 100 years ago, with the manufacture of cars, welded ships and other structures, pressure vessels and, finally, aircraft. At every step in the development of new structural types or forms, a similar sequence of events has been repeated: introduction of a new material to meet new performance requirements was followed by a sudden incidence of fatigue failures, a flare-up of fatigue research and a gradual accommodation to the new conditions by improvements in design, in testing, in fabrication and, after some delay, in the materials. The reason that material improvement is the last step in the sequence is that the approach of the metal-producing industry to material improvement has always been in terms of static strength properties rather than fatigue performance. Materials are produced to provide a higher static strength to weight ratio with little consideration for any other performance characteristics except plastic deformability. Inadequate dynamic performance in fabricated structures, when subsequently discovered, is then usually blamed on the designer or the fabrication processes.

The above sequence can be identified in the development of riveted steel structures for railroads, or locomotive axles as well as of automobile axles, of aircraft structures, of welded steel structures for ships, bridges and pressure vessels; it will undoubtedly be repeated in the development of the VTOL, the SST, the HST, the space shuttle and structures for deep submergence. Neither in welded structures nor in aircraft structures has this sequence in any way been completed: this is clearly demonstrated by the F-111 and C-5A experience. While improvements in design and fabrication are being extensively studied, both theoretically and experimentally, improvment of materials with respect to fatigue performance is making extremely slow progress.

The principal reason for this state of affairs is the almost complete lack of coordination and the gap in communication between research workers in metal physics, metal production engineers, structural designers, fabrication specialists and structural reliability statisticians. The metal producing industry usually resists pressure for improvement of fatigue performance as long as the produced material can be sold in quantity, unless such improvement is specially paid for by the prospective user. Even then, if the industry undertakes this task at all, it is with considerable reluctance because, up to the present time, effective guiding principles for the development of metals of superior fatigue performance are completely lacking.

Fatigue research by the metal producing industry, when existing at all, is minimal; there is, at best, some half-hearted conventional fatigue testing for not clearly specified purposes. In spite of the fact that more than 95 per cent of all reported structural failures are fatigue failures, the industry appears to have convinced the users that the principal approach to improved fatigue performance is through design, fabrication, and testing rather than through the specific development of fatigue resistance materials. The emphasis, in recent years, on crack propagation as the principal fatigue research topic illustrates this fact quite convincingly: materials evaluation for fatigue performance is based on crack-propagation rates in metals developed, produced and accepted on the basis of static strength properties that are not or are only vaguely related to fatigue performance.

Fracture mechanics has, in fact, been a boon to the metal producing industry: it has made the finite crack in a structure reputable and even fashionable. To raise the question of the possibility of developing and of producing a reasonably high-strength metal of commensurately high resistance of fatigue damage before the initiation of a propagating crack seems, at present, somewhat old-fashioned and may even raise the suspicision that the questioner does not know enough fracture mechanics. Nevertheless, and in spite of the fact that under current conditions of material development the structural designer has to live with cracked structures and therefore with fracture mechanics, the control of progressive damage under cyclic straining <u>preceding</u> crack propagation is the key problem in the development of fatigue resistance materials.

The stage of fatigue crack propagation, to the analysis of which concepts of fracture mechanics are applicable, extends in a well designed structure roughly over the last 40 to 60 per cent of its expected fatigue life. The significance of fracture mechanics based on continuum theory arises directly from the fact that at this stage of fatigue damage metallurgical microstructure is not of major significance. This can be inferred from the general form of the well-known and experimentally verified relation between the rate of crack propagation per cycle (dc/dN) and certain relevant material and design parameters

$$\frac{dc}{dN} \sim (G.\gamma.\sigma_y^{\ 2}.H)^{-1}.K^{\alpha} \qquad (1)$$

where the elastic shear modulus G, the strain-hardening modulus H, the yield stress σ_y, the surface energy γ and the exponent $2 < \alpha < 5$ are material parameters that depend on microstructure, while the stress-intensity factor K is essentially a design parameter.

Considering that a faulty design of some critical structural detail can easily raise K by a factor of two, leading, for the usual values of α, to a premature crack propagating at about 10 to 100 times the expected rate, it is easily seen that such increase cannot be compensated within the practical range of variation of the micro-structure dependent material parameters in competitive structural metals, even if α is substantially reduced towards the range of $2 < \alpha < 3$. Such a reduction of α, however, is not achieved by modification of the microstructure of a particular type of metal, but requires the selection of a material with a basically different mechanism of crack-propagation and thus of a basically different type of microstructure. Since a drastic reduction of α is usually accompanied by a reduction of σ_y, even the substitution of a different microstructure may not adquately compensate for faulty design, once the crack-propagation stage is attained. Fatigue crack propagation rates in a structure with fatigue sensitive deails are therefore much more effectively controlled by careful design and development testing of details and by the incorporation in the design of crack-stopping or crack-retarding elements than by materials selection on the basis of the evaluation of expected fatigue performance by S-N-diagrams or by fracture-toughness.

The very weak dependence on microstructure of the crack-propagation process in fatigue is further confirmed by the existence of the almost material-independent approximate relation between the plastic cyclic strain range ϵ_p and the number N of cycles to failure of unnotched metal specimens in "low-cycle" fatigue in which a large fraction of the fatigue life N is crack-growth

$$\epsilon_p N^n = \text{Const.} \qquad \text{for } N < 10^5 \tag{2}$$

where $0.5 < n < 0.8$ shows a weak dependence on microstructure. This equation can also be applied to crack propagation through the plastically strained material by assuming that, in rough approximation, the rate of crack propagation

$$\frac{dc}{dN} \sim \frac{c}{N} \tag{3}$$

and therefore, from Eq. (2)

$$\frac{dc}{dN} \sim c\epsilon_p^{1/n} \tag{4}$$

It should be pointed out that all of the above relations and conclusions do not necessarily apply to high-strength steels. The recent development of these steels has emphasized high tensile strength at reasonably high toughness with respect to fracture under unidirectional straining rather than cyclic straining. The fact that "fracture toughness" is not a direct measure of fatigue performance cannot be overemphasized. Particularly in the non-homogeneous microstructures characteristic of low carbon high-strength steels the strain-concentrating effect of the hard phases under reversed cyclic strain as well as of the diffusionless transformation processes damages the fatigue performance without affecting fracture toughness.

In view of the weak effect of microstructure on the crack-propagation process, an improvement in the fatigue life of a well-designed structure subject to a spectrum of forces of a certain intensity can only be expected from

(a) use of a material with the lowest possible value of γ at the highest possible yield stress;

(b) reduction of the cyclic plastic strain produced by the specified intensity of the spectrum;

(c) retardation of the damage initiation process in the microstructure so as to delay the start of the process of crack-propagation.

Of these three possibilities, it is the last which is likely to produce the most substantial improvement, the first two being concerned only with the crack-propagation stage.

Nuclei of fatigue damage develop very early in the course of cyclic straining as the result of the incompatibility of the locally anisotropic, incompletely reversed slip processes in the heterogeneous polycrystalline microstructure with the deformational restraints imposed by grain boundaries as well with the continuity of the macroscopic strain field. (Freudenthal, A. M., Summary of Conference Proc. G. M. Symp. on Internal Stresses and Fatigue, Detroit, Elsevier Publishing Co., New York, 1959, p. 428).

In uni-directional straining local incompatibility centers are smoothed out by widely dispersed slip, while the concentration of reversed slip in striations intensifies rather than relieves existing centers and creates new ones. In the course of cyclic straining such incompatibility centers become damage nuclei the severity of which increases with the number of applied strain cycles at a rate that depends on the extent of local micro-slip per cycle. (Ronay, M., On Strain Incompatibility and Grain Boundary Damage in Fatigue, Acta

Technica, Acad. Sci. Hung., vol. 54 (1966), pp. 199-218.) The momentary fatigue damage in the material is determined by the severity of existing damage nuclei and their volume or surface concentration. Severity of individual damage nuclei depends on microstructure, strain-amplitude and number of strain-reversals, while their concentration is also affected by the inhomogeneity of the strain field.

In polycrystalline metals damage nuclei develop both in the grain or cell boundaries and within the grains. Cell boundary nuclei are the result of incompatability of adjoining active slip system, while damage nuclei inside the crystal develop from the penetration of the surface by concentrated reversed slip accompanied by ridges, grooves and small extrusions into local material eruptions from a completely shattered surface (Wood, W. A., Fatigue Crack Initiation as viewed by Scanning Electron Microscope, Inst. for the Study of Fatigue, Fracture and Reliability, The George Washington University, Washington, D. C., Technical Report No. 1, January 1970). It is interesting to note that the shattering of the surface is visible only in oblique illumination. In vertical illumination only the slip traces appear, producing the apparent regularity of the slip deformation characteristic of the optical microscope and the replica technique of the electron microscope.

The relative importance of crystal slip and of grain or cell boundary restrains on the development of incompatibility centers depends necessarily on the mobility of the boundaries. Since the fatigue life of single crystals is much less affected by the elevated temperature than that of the polycrystalline aggregate, and since elevated temperatures affect the boundary mobility much more than transcrystalline slip, it might be assumed that at room temperature the more severe fatigue damage nuclei develop as the result of transcrystalline slip and surface shattering, while boundary nuclei become increasingly significant as the temperature increases. The cell structure itself, which is associated with a metastable "cyclic state" and is a function of strain-amplitude and temperature, has no direct relation to the damage process other than that of producing a deformed microstructure in which, by a yet unknown mechanism, micro-cracks are progressively developing.

It seems therefore convenient to keep the deformation phenomena under cyclic straining of the microstructure separated from "fatigue damage". Changes in the microstructure as well as changesin the stress-strain relation associated with deformation under cyclic straining are reasonably well understood; the mechanism of fatigue damage initiation is still not quite clearly understood, although very recent observations provide clear evidence of the intensification of the regions of incompatibility of reversed slip in adjacent crystals of different orientation which finally leads to a local break-up of the microstructure accompanied by microcracks. The initiation of fatigue damage by the formation of damage nuclei from deformation incompatibility centers and their coalescence into microcracks cannot be realistically dealt with either on the lattice defect scale or on a (elastic or plastic) continuum scale. Neither the concept of formation of atomic vacancies by intersection of moving dislocations and their coalescence into clusters, nor that of cracking produced by dislocation pile-ups have any apparent relation to what appears to be the process of fatigue initiation reflected by observation of the cyclically deformed microstructure. Clusters of atomic defects are hardly stable enough to form damage nuclei of the order of magnitude of 10^{-5} to 10^{-4} mm that appear to delineate the start of the fatigue initiation process. On the other hand, the shattered microstructure around a number of dispersed damage nuclei cannot be reasonably well represented by an elastic continuum in which a single crack propagates at a velocity that depends on its elastic stress-intensity factor. The concept of a perforated sheet in which the damage nuclei ("pores") represent the performations, and crack propagation proceeds between preferentially aligned nuclei, which has been suggested by Wood (Wood, W. A., Systematic Microstructural Changes peculiar to Fatigue Deformation, Acta Met., vol. 11, 1963, p. 643.) for the H-stage, seems to provide the most reasonable model of the fatigue crack initiation process. It seems justified to assume that an applied or a residual tensile mean stress will significantly facilitate this process by reducing the energy release rate associated with crack extension between nuclei.

From the designers' point of view, fatigue resistance in the H-stage is the significant property for effective maerial selection. Once it is admitted that the initiation of a fatigue crack cannot be prevented, the effect of materials selection is secondary to that of reduction of crack-propagation rate by design and development testing of fatigue sensitive details. Only under the assumption that crack-initiation in these critical locations can be prevented does selection of a fatigue resistance material become significant not only with respect to structural safety but still more with respect to economy of maintenance coupled with improved fleet readiness. The development of fatigue resistance materials in which crack-initiation is significantly retarded is the only certain way to a drastic reduction of maintenance costs and of the uncertainly of life prediction associated with highly fatigue sensitive materials.

Intensity and concentration of damage nuclei are obviously most severe at the location of the largest strain amplitudes.

In the case of a long range transport the most damaging strain cycles are produced by the ground-air-ground cycle; with an assumed average time between landings of 3 hours and 30,000 hours design service life, their number is of the order of magnitude of 10^4. Considering that the associated nominal strain amplitudes in the critical members may attain values of 0.1 to 0.15 per cent (which would be in F-range), the magnification of these values by local stress concentrations might easily reach 0.5 per cent with an associated fatigue life at the upper limit of the H-range ($N \sim 10^5$). Considering that in this range observations show development of severe damage nuclei at less than 10 per cent of this limit, it would appear that fatigue damage initiation in aircraft structures arises from interaction, at the critical locations, of the effects of the multitude of flight induced strain-cycles (that are either in the F or the S range) with the damage nuclei that are gradually intensified by the almost periodically induced ground-air-ground cycles and other less frequent but more damaging accidental cycles arising from thunderstorm gusts or clear-air turbulence. This interpretation is supported by results of spectrum fatigue tests in which the ground-air-ground cycles produce a highly disproportionate amount of damage, a result that should completely shatter any remaining belief in the usefulness of Miner's uncorrected rule. If therefore this damage accumulation in the H-range could be signifcantly retarded, the total fatigue life might be increased by several orders of magnitude.

Improvement of the fatigue resistance by retardation of the formation of damage nuclei in the H-range would require a drastic reduction of the extent of slip in this range which could be achieved by grain-refinement that remains stable under reversed straining. A very fine-grained structure stabilized by a finely dispersed alloying element is obviously associated with a high elastic limit that is the result of stable pinning of the structural defects by the dispersed particles. However, in metals elasticity up to high stress levels under unidirectional and reversed straining is an anomaly that can be expected only if the pinning of the defect structures is reasonably stable under all conditions of straining. The rate of fatigue damage initiation will depend on the rate of loss of this stability under reversed cyclic straining as a function of strain amplitude and of frequency.

Such loss will be most pronounced in pure torsion where the stabilizing effect of a hydrostatic stress component does not exist. Instability can therefore be demonstrated best by the super-position of an axial load on cyclic torsion since this load magnifies the instability effect by producing the "cyclic creep" which is a manifestation of the microstructural instability. (Wood, W. A., Yield and Second Order Effects induced by Cyclic Torsion in Copper under Tension, Acta Met., vol. 15, 1967).

In a recent study of the fatigue performance of some high yield low-carbon ferrous metal alloys (Ronay, M. Fatigue Performance of High Strength Steels as Related to their Transformation Mechanism, Proc. Air Force Conf. on Fatigue and Fracture, Miami, Dec. 1969), the desirability of a very fine-grained, homogeneous, stabilized microstructure has been demonstrated by the truly outstanding performance of the quenched and tempered 5 Ni-Cr-Mo-V (HY130) steel.

In another study (Wood, W. A. and Mason, W. P., Fatigue Mechanism in Iron at Ultrasonic Frequency, J. Appl. Phys. vol. 40 (1969), p. 4514), the normally neglected effect of the frequency of cyclic straining on the stability of dislocation pinning has been demonstrated by exciting low-carbon iron specimens at ultrasonic frequency. While no indication of any change in microstructure could be discovered at strain amplitudes up to $13x10^{-4}$ and conventional frequencies (1700 cpm), isolated slip was intense at ultrasonic frequency (17,000 Hz) already at amplitude of $2x10^{-4}$, microcracks appearing at amplitude $4x10^{-4}$, which is less than one third of the "safe" limit at conventional frequencies. These observations support the interpretation that fatigue damage initiation depends on the level of the stable elastic limit that can be produced by dislocation pinning. The stability of this pinning prevents the breakaway of dislocations at low frequencies of cyclic straining and within a certain range of strain-amplitudes. At ultrasonic frequencies resonance of dislocation loops oscillating about the pinning points may lead to local break-away at points at which the applied energy will concentrate and produce intense slip followed by microcracks.

The close interrelation between the fatigue performance of the structure and the changes in the microstructure of the metal are illustrated by these examples, which thus demonstrate the necessity of the interdisciplinary approach to fatigue to which the work of the Institute for the Study of Fatigue and Reliability has been devoted during the years of its operation at Columbia University.

2. Activities of the Institute

The Institute for the Study of Fatigue and Reliability was established at Columbia University in April 1963 under joint sponsorship of the Office of Naval Research and the Materials Laboratory of the Air Force, WPAFB, with an initial grant from the Advanced Research Projects Agency, for the purpose of developing an interdisciplinary approach to fatigue research on the basis of close cooperation between research workers in different fields working within the same group. The principal emphasis in the work of the Institute has been on the study of the physical mechanism of damage initiation, with a view of establishing the principles for the rational design of metal alloys of superior fatigue performance and for their structural evaluation on the one hand, and on the development of advanced methods of fatigue design and of reliability analysis and demonstration on the other. In view of the large volume, past and current, of straight fatigue testing of standard test specimens in industrial, government and many university laboratories no testing of this type was, in general, done by the Institute.

The work of the Institute was concentrated in three principal areas:

I. Metal Physics and Micromechanisms of Fatigue.

II. Experimental and Theoretical Solid Mechanics.

III. Experimental and Theoretical Structural Integrity and Reliability.

The principal accomplishments of research workers of the Institute in these three areas are outlined in the following by listing the principal facts established or subjects studied.

I. Metal Physics and Micromechanisms.

(a) The crucial importance in simple metals of the concentration of reversed slip in the crystal grain as well as of the strain incompatibility centers developing along grain boundaries due to reversed slip in neighboring grains for the initiation of fatigue damage has been clearly demonstrated and the most important process of development and spreading of fatigue cracks in the microstructure identified as a process that has some similarities to the tearing of a sheet or body perforated by "micropores" developed around strain incompatibility centers.

(b) The crucial importance, in complex metal structures, of the concentration of reversed slip due to the heterogeneity of the microstructure as well as by diffusionless phase transformation processes preceding or accompanying the cyclic straining.

(c) The crucial importance for the initiation of fatigue damage of the instability of the elastic limit of structural alloys under reversed cyclic straining.

(d) The damaging effect of ultrasonic frequencies.

(e) The damagingeffect on the fatigue of metal-metal composites of the conctration of reversed strain by the hard reinforcement interfaces.

II. Experimental and Theoretical Solid Mechanics

(a) The existence and basic significance of second-order effects in strain-hardening metals and their relation to fatigue in torsion and to the acceleration of creep by reversed cyclic straining.

(b) The significance of the demonstrated second-order effects on the formulation of a yield condition, loading function and flow-rule and on the basic assumptions of the theory of plasticity.

(c) The advantage in using second-order effects for the observation and measurement of deformational and structural instability, particularly in fcc metals.

III. Experimental and Theoretical Structural Integrity and Reliability.

(a) The development of a method of reliability analysis in fatigue of redundant structures.

(b) The establishment of a method of fatigue evaluation of high-strength structural steels.

(c) The formulation of design criteria on the basis of the probability distribution of the safety factor.

(d) Structural reliability analysis based on the theory of random processes applied to various problems.

66 technical reports on various aspects of the Institute research have been issued, and some 60 papers published by members of the Institute in the technical and scientific literature.

Nine doctoral dissertations, three in physical metallurgy, two in solid mechanics and four in reliability theory and eight M.S. theses have been completed under sponsorship of the Institute, and the respective degrees awarded by the University.

The Institute has also sponsored regular university seminars with graduate credit in the Fall and Spring sessions, given by Profs. W. A. Wood and W. P. Mason respectively. Prof. Mason's seminar notes have recently been published as a book ("Physics of Interaction Processes", Academic Press, New York, 1966), Prof. Wood's seminar notes are being published by Prentice Hall. Three special Institute seminars were arranged to discuss problems of special concern to the Sponsoring Agencies of the Institute. In April 1969 the Institute organized an International Conference on Structural Safety and Reliability at the Smithsonian Institute in Washington, D. C.

Since its inception the Institute has been host to eight foreign and three U. S. senior research workers invited to pursue special research problems in fatigue. It has also been host to ten post-doctoral research workers from U. S. and foreign Universities. Several former graduate students trained by the Institute are now employed by the Department of Defense in positions for which such training is of primary importance. It is therefore believed that the Institute has succeeded in accomplishing its dual purpose of advanced interdisciplinary research in fatigue and reliability and advanced training of graduate students in these fields.

In 1967 the Institute entered into a joint research program on fatigue performance of high strength steels with the Swiss Federal Institute of Technology, the Federal Institute for Materials Testing and the Swiss Aircraft Works, in the framework of a general Exchange Program of Columbia University with the Swiss Federal Institute of Technology, in Zurich. Exchange of research workers between the cooperating institutions has been of considerable benefit to all cooperating institutions and results of considerable significance concerning the relative structural fatigue performance of various high strength steels have been obtained and reported.

The work of the Institute has reflected in a balanced way, the research interests of the Navy and the Air Force which overlap considerably in the field of fatigue.

The Institute has also been called upon for information, lectures and consultations by the Office of Naval Research, the Materials Laboratory of the Air Force, WPAFB, the Tinker Air Force Base, Oklahoma, the Marine Engineering Laboratory, Annapolis, the Special Projects Agency of the Dept. of the Navy, the Federal Aviation Agency and the Boeing Aircraft Company.

The financial support of the Institute has come from the Advanced Research Project Agency, the Office of Naval Research and the Air Force Material Laboratory. The University has been providing the space and most of the equipment at an overhead rate substantially below the level negotiated through the University.

3. Staff

The staff of the Institute varied over the years of operation depending on the level of financial support as well as on the number of doctoral students interested in research under the Institute sponsorship.

The following is a list of the staff of the Institute as well as of all graduate students who obtained their degree under the auspices of the Institute.

Permanent Staff

Prof. J. M. Garrelts, Administrative Director
Prof. A. M. Freudenthal, Technical Director
Prof. M. Gensamer, Metallurgy
Prof. W. A. Wood, Metallurgy
Prof. W. P. Mason, Acoustics and Solid State Physics
Dr. M. Ronay, Metallurgy
Dr. R. A. Heller, Mechanics and Reliability
Prof. M. Shinozuka, Reliability

Visiting Staff

Prof. W. Weibull, Royal Inst. Tech. Stockholm (ret.) 1963-64.
Dr. D. I. G. Jones, Vickers Armstrong, Ltd., England; Air force Materials Lab., WPAFB, 1963-65.
Prof. G. K. Korbacher, University of Toronto, 1963-64.
Mr. J. Branger, Swiss Federal Aircraft Works (F+W) Emmen, 1964.
Prof. W. H. Munse, University of Illinois, 1964.
Dr. J. C. Grosskreutz, Midwest Research Inst., 1964-65.
Mr. D. M. Forney, Air Force Materials Laboratory, WPAFB, 1964-65.
Prof. R. Cerf, University of Strassbourg, 1965.
Dr. G. Jacoby, German Aeron. Res. Lab. (DVL), 1966.
Prof. I. Konishi, Kyoto University, 1967.
Dr. J. Wehr, Warsaw University, 1969.

Post Graduate Research Associates

Mr. L. E. Jarfall, Royal Inst. Tech., Stockholm, 1963-64.
Dr. M. Ohnami, Ritsumeikan University, Kyoto, 1963-64.
Dr. K. Nagai, Hiroshima University, 1963-64.
Dr. A. Nishimura, Kobe University, Kobe, 1964-65.
Dr. M. Hakuno, University of Tokyo, 1964-65.
Dr. J. T. P. Yao, University of New Mexico, 1964-65.

Dr. Y. Sato, Railway Research Institute, Tokyo, 1965-66.
Dr. H. Itagaki, Yokohama National University, 1965-67.
Dr. M. Hanai, Kyushu University, Fukuoka, 1966-67.
Dr. Volker Esslinger, Fed. Inst. of Tech., Zurich, 1968-69.

Technicians

Mr. G. Anderson, Laboratory Manager
H. Meyer, Machinist
P. Welterlin, Laboratory Technician
S. Lapides, Laboratory Technician (1966-67)
C. Cramer, Laboratory Technician (1966)
A. Rosenberg, Research Assistant

Secretary

Judith A. Beardsley

Graduate Students

For Ph.D. or D. Eng. Sc. Degrees:

Dallal, H., Metallurgy (1969)
Gates, R., Metallurgy (1967)
Gou, P. R., Eng. Mechanics (1968)
Murro, R., Eng. Mechanics (1966)
Payne, A. O., Eng. Mechanics (1965)
Reimann, W., Metallurgy (1966)
Thakur, L., Industrial Eng. (1964)
Wang, P. Y., Eng. Mechanics (1967)
Yang, J., Eng. Mechanics (1968)

For M. S. Degrees:

Chao, N. Electrical Eng. (1966)
Chen, L., Civil Eng. (1967)
Donat, R., Civil Eng. (1966)
Fisher, R., Eng. Mechanics (1966)
Heller, A., Math. Statistics (1963)
Liu, J., Civil Eng. (1966)
Loshigian, H., Civil Eng. (1964)
Shank, W., Civil Eng. (1966)

4. Reports

The following is a list of TechnicalReports issued by the Institute to date:

No. 1. Shinozuka, M., On Upper and Lower Bounds of the Probability of Failure of Simple Structures under Random Excitation. December 1963.

No. 2. Freudenthal, A. M. Weibull, W. and Payne, A. O., First Seminar on Fatigue and Fatigue Design. December 1963.

No. 3. Wood, W. A., Reimann, W. H. and Sargant, K. R., Comparison of Fatigue Mechanisms in Bcc Iron and Fcc Metals. April 1964.

No. 4. Heller, R. A. and Shinozuka, M., Development of Randomized Load Sequences with Transition Probabilities Based on a Markov Process. June 1964.

No. 5. Branger, J., Second Seminar on Fatigue and Fatigue Design. June 1964.

No. 6. Wood, W. A. and Reimann, W. H., Room Termperature Creep in Iron under Tensile Stress and a Superposed Alternating Torsion. June 1964.

No. 7. Ronay, M., Reimann, W. H. and Wood, W. A., Mechanism of Fatigue Deformation at Elevated Temperature. June 1964.

No. 8. Freudenthal, A. M. and Shinozuka, M., Upper and Lower Bounds of Probability of Structural Failure under Earthquake Acceleration. June 1964.

No. 9. Ronay, M., On Strain Incompatibility and Grain Boundary Damage in Fatigue. August 1964.

No. 10. Shinozuka, M., Random Vibration of a Beam Column. October 1964.

No. 11. Wood, W. A. and Reimann, W. H., Some Direct Observations of Cumulative Fatigue Damage in Metals. October 1964.

No. 12. Freudenthal, A. M., Garrelts, J. M. and Shinozuka, M., The Analysis of Structural Safety. October 1964.

No. 13. Ronay, M. and Freudenthal, A. M., Second Order Effects in Dissipative Solids. January 1965.

No. 14. Shinozuka, M. and Nishimura, A., On General Representation of a Density Function. February 1965.

No. 15. Wood, W. A. and Nine, H. D., Differences in Fatigue Behavior of Single Copper Crystals and Polycrystalline Copper at Elevated Temperatures. February 1965.

No. 16. Ronay, M., On Second Order Strain Accumulation in Torsion Fatigue. February 1965.

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