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CAIRO - EGYPT

1 # PROPOSED WORKING LIFE APPROACH FOR WELDED JOINTS : WITH
2 # APPLICATION TO AIRCRAFT STRUCTURES .

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4 ABSTRACT

A proposed working life approach for welded joints in aircraft structures is investigated. This approach is based on the assumption that the crack propagation will be under clear monitored survey. The repairs, however, should be carried out at a level long before the welded joint may become in jeopardy. Risk of failure and the cost effective of this risk are also included within the proposed approach.

NOMENCLATURE :

C_E is the present value of the expected economic losses.
F is a scatter factor.
k is a measure of hazard potential.
N_a is the delay time between deciding a deviation exists and introducing a compensatory adjustment =0, if there is no delay time.
N_b is the number of adjusting devices.
P_{nj} is the change introduced by adjusting device n at time j.
p is the relative frequency distribution.
p_f is the probability of failure.
$R(.)$ is the reliability function.
s is the standard deviation.
T is the inspection time.
t is the fatigue life.
t_1 is the fatigue life based on safe-life concept.
V_2 is the characteristic fatigue life.
v^2 is the coefficient of variation.
X_T is a random variable denoting the process level at time t.
α is related to the coefficient of variation v^2.
δ_k is a r ndom variable denoting adjustable cause magnitude, =0, unless an adjustable cause arrival is indicated at k.

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Θ_{nj} is a parameter depends on the interaction among the P_{nj} and the current process level.

ω is the interaction factors.

ε_T is a random variable representing the effect of change of variation.

μ is the desired value of the characteristic mean.

σ is the stress amplitude.

1. INTRODUCTION :

In the field of design of welded structures, it is of great importance to realise and to appreciate the risk analysis approach. In recent years, probabilistic tools have been developed and introduced in designs of welded structures. This is mainly due to the increased demand and applications of welding as a fabrication process. Several variables should be considered when designing a welded structural component to withstand cyclic fatigue spectrum of loading [1] . Risk analysis as a rationale for design of welded joints has been investigated and described in Refs. [2] and [3] . The conclusion drawn in Ref. [3] , however, concerning the welded structure is still valid, viz, in third world countries, e.g., the Arab countries in general, the designer, the fabricator, and the owner may face the problem of applying of different schools of welding codes and different standards of quality control.

The unification and the evolution of the Arab Codes of Welding and Quality Assurance Standards should be the target of the industrial and research establishments in Arab countries. Also, it has been stated in Ref. [3] that the basic problem in identifying the quality assurance and welding standards comes from the variation, in not only the pricipals, but also in the methodolgy of the application itself. This stimulates from the discrepancies within the different schools of non-destructive testing techniques and the welding codes. If for example the welded product is to follow the German welding code of welding standards, thus it should be verified by the DIN standards. If however, the same product is fabricated from the same material but welded within the Japanese code, then the JIS standards should be applied. The same rules apply to the A.W.S., the U.S.S.R. and the British standards.

As a result of variations in the requirements of each of the above mentioned codes and standards, the efficiency of the welder, the inspector and the product itself will dramatically be affected. The cost of production will be increased, the speed in the production line will be decreased, and thus there is a great need for the unification of codes of practice and quality assurance standards in all Arab countries. This code will serve in increasing the efficiency of welders and the cost of production will thus be brought to a minimum.

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The present paper investigates a proposed approach which is based on an estimated life which allows for minor fabricating defects to be present and monitored until repairs are to be carried out. This approach is thought to pave the way for the evolution of the Arab Welding Standards and Quality Assurance Codes.

2. STATE OF THE ART :

Aircraft structural design philosophy has been expanded in Ref. 4 to include requirements for fatigue evaluation and fail-safe strength. Another approach to the fatigue problem in aircraft joints has been devised in Ref. [5] . However, the approach is based on the concept of fatigue ratio. However, the fatigue ratio which represents a very good guide for designers, cannot be taken as a basis for performance evaluation. This may be due to the fact that even if an adequate fatigue ratio may very well withstand satisfactorily the repeated service loads, this will require a sufficiently high safety factor [6, 7] and [8]

Monitoring of aeroplanes in flight is necessary [9] , whether the aeroplane is designed according to the safe-life or the fail-safe concepts. Both the aerospace and the maritime industries resemble each other. They have many problems in common and suffering from similar drawbacks. For example problems such as weight savings, propulsion, drag reduction and structural life and reliability are common in both fields. Nevertheless the industrial solutions to these problems are significantly different. The unique nature of aerospace needs has resulted in a drive toward new technology, generating and requiring fracture mechanics calculations [10] , and crack propagation analysis of practical materials [11]. Also, in the aerospace industry, fatigue and fracture are commonly separated conceptually into two somewhat overlapping disciplines. For example fatigue studies include the durability of material under repeated random loads [12] . Therefore the fatigue life of an aircraft structure is defined as the period required to start a crack, e.g., safe-life analysis. Once a crack appears, its growth under static additional cyclic load is governed by the equations of fracture mechanics. Thus fatigue can be related to economics while fracture is related to safety. The appearance of the crack must be monitored under thorough survillance till the defected component is required to be repaired or replaced. Consequently, this imply that long fatigue lives will result in low replacement or repair costs. Once a crack appears and starts to grow the strength will remarkably be reduced.If the crack is allowed to grow longer the strength is expected to drop significantly. Fracture mechanics technology is not only providing ways to estimate crack growth rates, but also estimates the load at which a given crack will propagate unstablly [13] . Unstable crack growth means failure of the structural element [14] . Therefore, the monitoring and inspection periods should be made regularly and long before the structure reaches the immobilization stage.

3. WELDING PROCESSES AND N.D.T. METHODS :

Since world war II, the world industry at large, uses extensively the welding process for fabrication of structures. In the early days most welded structures were put into service after very few non-destructive inspections. However, some welded structures experienced failures, most of which originated from weld defects. Therefore, the need was recognized for developing reliable methods for non-destructive inspection of welds. These methods have been based on better understanding of mechanisms of fractures which have led to the development of fracture mechanics theories on the one hand and to the improvement in fracture toughness of materials on the other [15] .

Designers and owners might expect that repair of welds have been reduced considerably. Nevertheless, the total cost of fabrication of primary structures has remarkably increased. The most significant portion of the cost increases, even after adjusting for the effect of inflation, comes from the inspection and repair procedures after welding.

The technology of non-destructive testing still advances such that an increasing number of small defects can be detected. Many of these defects would have gone undetected in previous years. Once defects in welded structures of an aircraft are detected, there is a tendency that defects should be repaired. If, however, this idea is to be carried out to its extreme, it means that as the testing equipment becomes more capable the number of repairs will increase. This attitude will lead to more stringent situation. If this current trends continues there will be a further significant increase in the repair costs. Although the direct cost required for inspection and repair may not be great, the financial loss due to the fact that aircrafts are laid idle can be enormous. Suppose that defects are found in a component of a secondary important structure in an aircraft structure, thus the repair work will certainly delay the use of such aircraft. The component may work satisfactorily without even repair, but some problems may be developed later on. Therefore an engineering and economical compromise must be made. Sometimes repairs may seem to be costly. In some instances, the repairing processes may seem to be impossible.

Thus the designer, the fabricator and the owner must all be provided with a basic tool to decide on whether and when repairs must be carried out. This can be provided by developing a design rationale for accepting some defects of minor importance in secondary stressed members based on the fact that these defects are not harmful. This rationale together with the improvement in the reliabilty of welding operations is aimed at reducing weld defects. The economical and engineering aspects are the important factors in choosing the design rationale based on life estimates.

4. DRAWBACKS IN CURRENT CONCEPTS :

Infinite-Life Design Concept :

This is the first fatigue design criterion. It is still however, applied in cases where the stress history is well defined. If the loads are of a stochastic nature as is the case for aircraft this design concept is overly conservative [16] and [17] and [18]. Therefore, this concept is hardly in use nowadays.

Safe-Life Design Concept :

This concept may be expressed in terms of fatigue failure probability of extremely remote in occurrance. Conditions which make safe-life design imparative are:
- the component in question is vital to the load carrying capacity of the structure, e.g., lack of redundancy [19] , [20].
- the structure is difficult and expensive to inspect and/or even to repair, e.g., internal connections in fuselage.
- a fatigue failure may impair the safety by causing fire and explosion hazards, leakage and reducing the maneuverability of the aircraft.

Fail-Safe Design Concept :

This design criterion is used to describe components or structural parts for which conditions requiring safe-life design do not apply. The underlying philosophy is that fatigue cracks develop slowly and may be detected and repaired in due time, provided that proper inspection routines can be carried out [21] . The use of this design approach is very restricted, due to the fact that inspection of aircraft structures is extremely restrictive as standards and expensive in terms of cost [22] .

5. PROPOSED WORKING-LIFE :

Based on the following assumptions the proposed- working-life approach has been derived. Figures 1 and 2 show schematically representation of the steps and assumptions of the proposed approach. This approach is thought to be an evolution of design of welded structures to ensure adequate safety and reliability.

1. The resulted fabricated defects in an aircraft structure is such that they will not lead to catastrophic failure and loss of life [23] . The critical parameters involved in implementing the proposed approach are the defined crack or defect length, the inspection period, the crack growth rate, the residual static strength and the cost of repair.

The cost of reliability will be determined in the course of calculations and to be compared with the cost of repair.

2. The components designed by this concept are assessed to be inspectale in the course of routine service inspections 24 .
3. Based on the assumption that the first structures that will fail in fatigue out of a statistical population of structures subject to similar operational loading spectra are the weakest structures, may be represented by the reliabilty function of equations(1), after Ref. 25 .

$$R(t) = \exp\left[-(t/V)^{\alpha}\right] \qquad (1.a)$$

Hence,

$$p_f = 1 - R(t) = 1 - \exp\left[-(t/V)^{\alpha}\right] \qquad (1.b)$$

The index α can be obtained from Fig. 3 corresponding to a defined value of coefficient of variation v^2, .

4. The characteristic function of the detection of a defect during testing may be that given by equation(3), 26 .

$$X_T = \mu + \sum_{k=1}^{T} \delta_k + \sum_{n=1}^{N_b} \sum_{j=1}^{T-N_a} \theta_{nj} \cdot P_{nj} + T \qquad (2)$$

The characteristic function given by equation(3) above is to be determined according to the conditions, type and technique of testing method, viz;

- Chance causes of variations continue to be too numerous, too small and too frequent to justify a response.
- Adjustable causes, which are random in arrival and magnitude, and can occur relatively infrequently, but are large enough to make compensating adjustment economically desirable.
- Assignable causes of variation cannot be compensated for and must be found and removed.
- Measurement causes of variation caused by the testing equipment and adjusting variation caused by the adjusting device are to be minimum.

5. The risk cost of an aircraft structure refers to the present value of the expected economic losses resulting in its failure [27] . It is, therefore, useful to express the risk cost in terms of the replacement cost C of the structure. The economic component of the hazard potential is expressed as a result of a multiple of C, equation(3).

$$C_m = k \cdot C \qquad (3)$$

The quantity of k in equation(3) may be as high as 10 to 100 for the case of aircrafts. The expected future loss due to failure is thus as shown by equation(4), [27] .

$$\text{Risk cost} = f \cdot t \cdot P_f \cdot k \cdot C \qquad (4)$$

This risk cost must be less than the ecnomic loss cost and the cost of repairs.

6. Based on S/N design curve which lies in a range between the safe-life and the fail-safe curves distant α.s from the mean line. The value of (α) could be obtained from

Figures 3 . These figures have been determined from data based on economical and engineering reasons. However, the S/N curve must be determined corresponding to the estimated probability of failure, shown by equation(1.b) above. The S/N curve is therefore, as shown in Table 1, for various welded details collected from Ref. [1,2, 30 to 35], and equation(5).

$$\log_{10} N_i = \log_{10}\gamma - \alpha_w . s - \delta . \log_{10} \sigma_i \qquad (5).$$

The working life of the component can be detrmined from equation (6).

$$t = -1/ \int_0^\infty \frac{1}{N_i} . \frac{\partial(n_i . p_i)}{\partial \sigma_i} . d\sigma_i \qquad (6)$$

The value of n_i in equation(6) is the number of cycles of exceedances of stress σ_i in the stress spectrum, and the value of p_i is the frequency probability value.

The trouble free life (t_E) of the component can be estimated from equation(7).

$$t_E = t . F \qquad (7)$$

The value of F in equation(7) must be less than unity and should however cover all the uncertainties associated with the designed component, inspection tests, material and fabrication procedures.

The aircraft has to be built for a strategic purpose and the human life is thus of great importance. However, for certain economical reasons which are to be met, the target life is thus to be based on safe-life design approach. This target life must be compared with the trouble free life obtained by equation(7). If the calculated target life is greater than that of the trouble free life thus the design of the welded joint is said to be correct. If the life calculated on the basis of safe-life is less than that obtained from equation (7), thus a modification or series of alterations are needed in order to reach the conclusion of equation(8).

$$t_E \geq t_1 \qquad (8)$$

After being sure that equation(8) has been fulfilled, the designer must carry out fracture mechanics calculations. The usefulness of fracture mechanics lies in the prediction of critical crack size for a given component from a knowledge of the fracture toughness of the parent material, welds and weld heat affected zones. Figure 4 shows schematically for a welded joint , to estimate the reiability of a component containing defects. Figure 5 shows the flow diagram of the acceptance criteria of welded defects proposed in Ref. [29] . If the critical flaw size is greater than the minimum size that can be detected by the N.D.T. techniques in operation, premature failure should be prevented provided that crack growth does not occur due to stress corrosion or other phenomena [30] . If the critical flaw size is less than that detected, the material should be changed to one with greater fracture toughness and the calculations in step 6 must be repeated till good justification is to be reached.

6. CONCLUSIONS :

Due to size limits of the paper the applications of the investigated approach is to be published in the near future . Nevertheless the work represented in this paper can certainly be applied in the design of welded components in aircrafts. The following are general conclusions drawn from the presented work.

1. Unification of the different welding codes currently applied within the Arab countries will ease in sorting out most of the welding problems and hence this will lead to increase in efficiency and productivity of the welding industry.
2. A working-life approach based on a certain calculated risk of failure and the cost effective of this risk has been investigated and proposed.
3. It is believed that the proposed approach provides a format for the effectiveness of a strategy for failure prevention of welded components in aircraft structures.
4. The proposed approach has an advantage over the current concepts in that it provides a frame work for achieving balanced designs of aircraft welded components in which no single contributing hazard or cost component which is unduly dominates the hazard mitigation effort.

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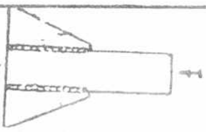
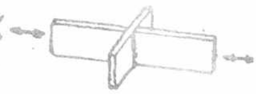
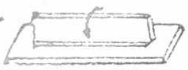
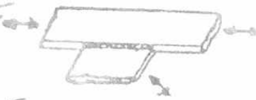
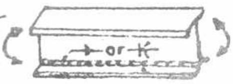
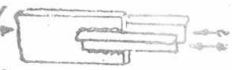
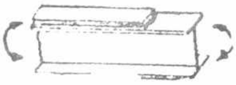
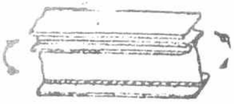
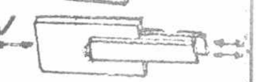
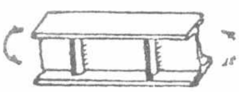
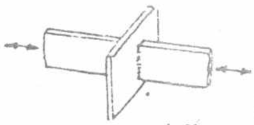
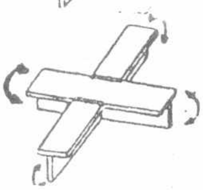
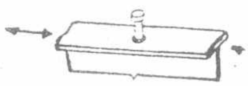
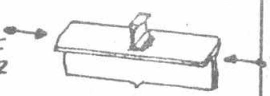
TABLE 1 : IMPORTANT WELD DETAILS, EQUATION(5).

JOINT DETAIL AND CLASS	6	$\log_{10}$	s	JOINT DETAIL AND CLASS	6	$\log_{10}$	s
B 	4.35	14.317	0.657	X 	3.94	14.276	0.458
F 	5.02	19.453	0.605	F 	3.48	12.836	0.605
D 	5.77	19.322	0.617	E 	4.63	15.895	0.561
F_2 	6.08	19.922	0.592	W 	3.73	13.51	0.654
G 	3.25	12.342	0.662	W 	4.03	13.643	0.654
W 	6.06	19.919	0.654	W 	7.49	13.484	0.654
F 	4.11	15.017	0.605	X 	4.03	14.276	0.458
E 	7.44	23.14	0.561	X 	3.53	12.659	0.458
G 	6.13	19.448	0.662	X 	3.15	12.677	0.458
F_2 	3.98	18.856	0.592	F_2 	3.26	12.791	0.592
G 	4.23	15.665	0.662				

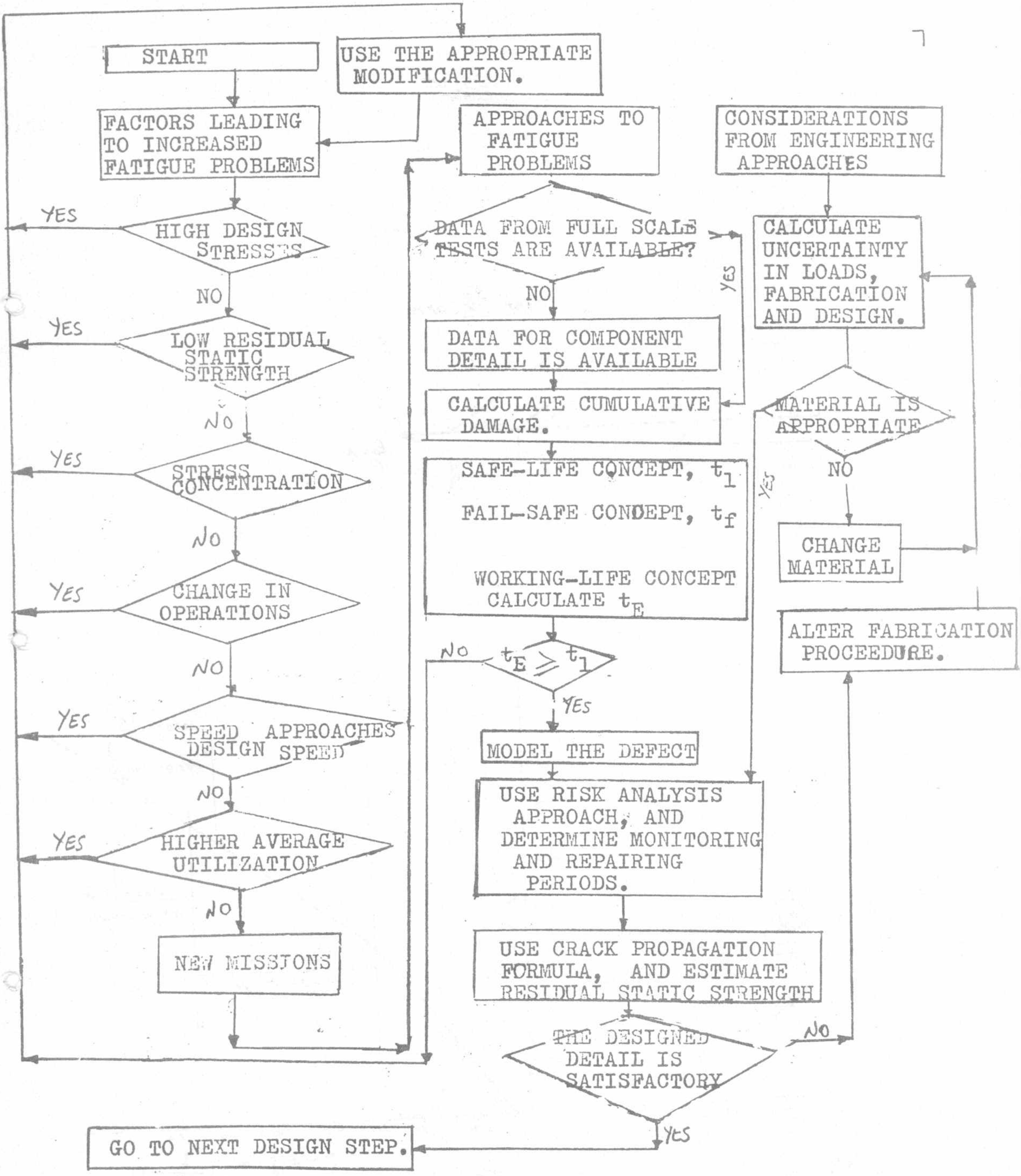


FIG. 1 : DESIGN PROCEDURE INCORPORATING THE PROPOSED WORKING-LIFE APPROACH.

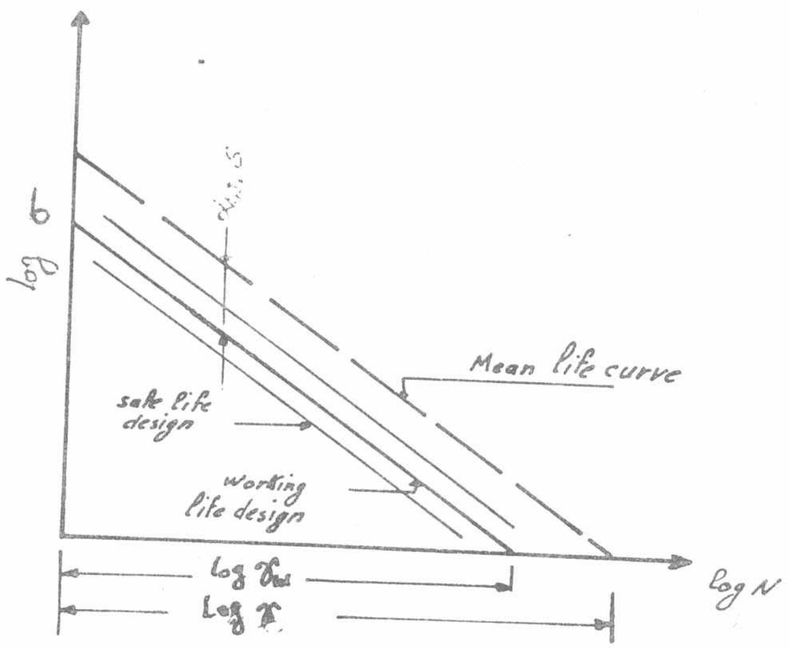


Fig. 2.

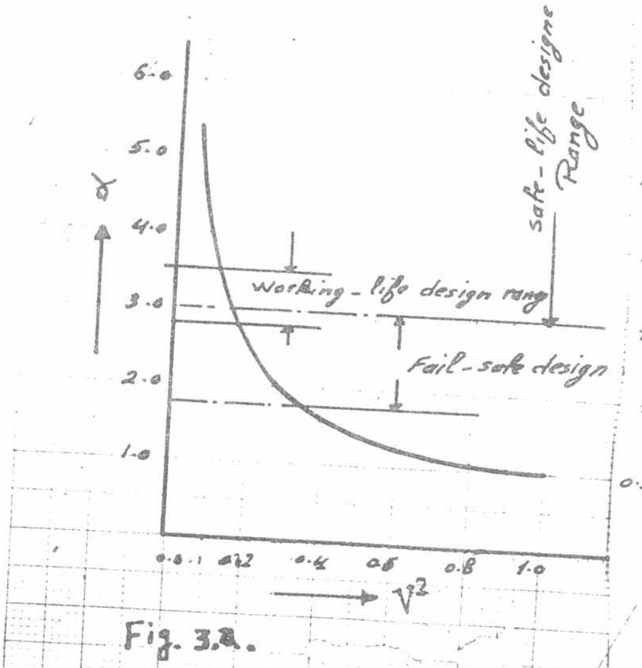


Fig. 3.a.

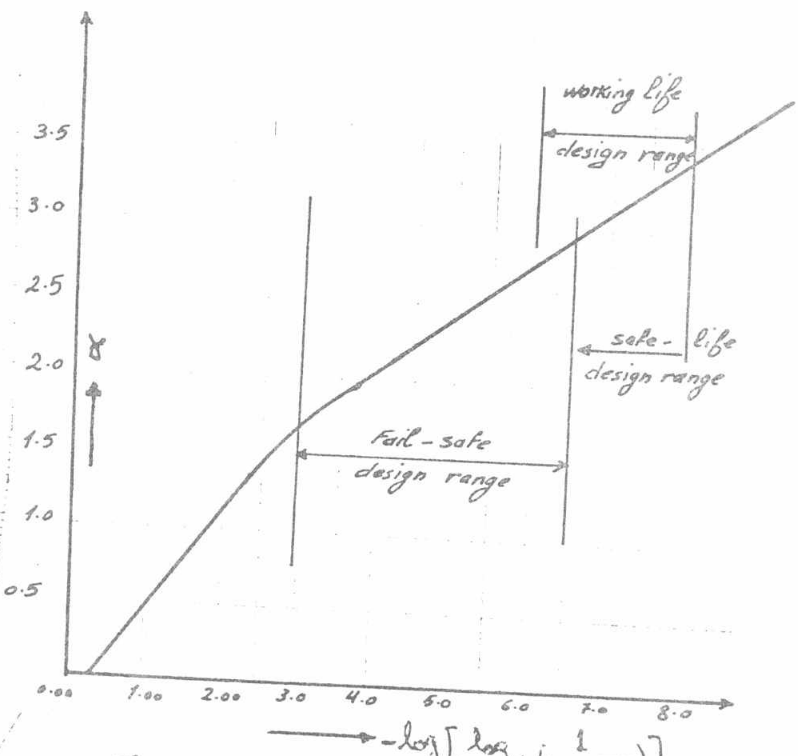


Fig. 3.b.

a_{al} is the accepted limit of tolerable crack length,
a_{fw} is the resultant crack length at failure, after inspection and repair
a_f is the crack length at failure .
A(a) is the capability and S(a) is the demand.

1 Area defines the allowable fracture probability, the capability

2 Welding procedure gives probable existance of flaws in a material,

3 Area defines the probable existance of defects with different sizes after inspection and repair,

4 Area defines the distribution of critical flaw size from measured data related to fracture toughness variations in time and different loads.

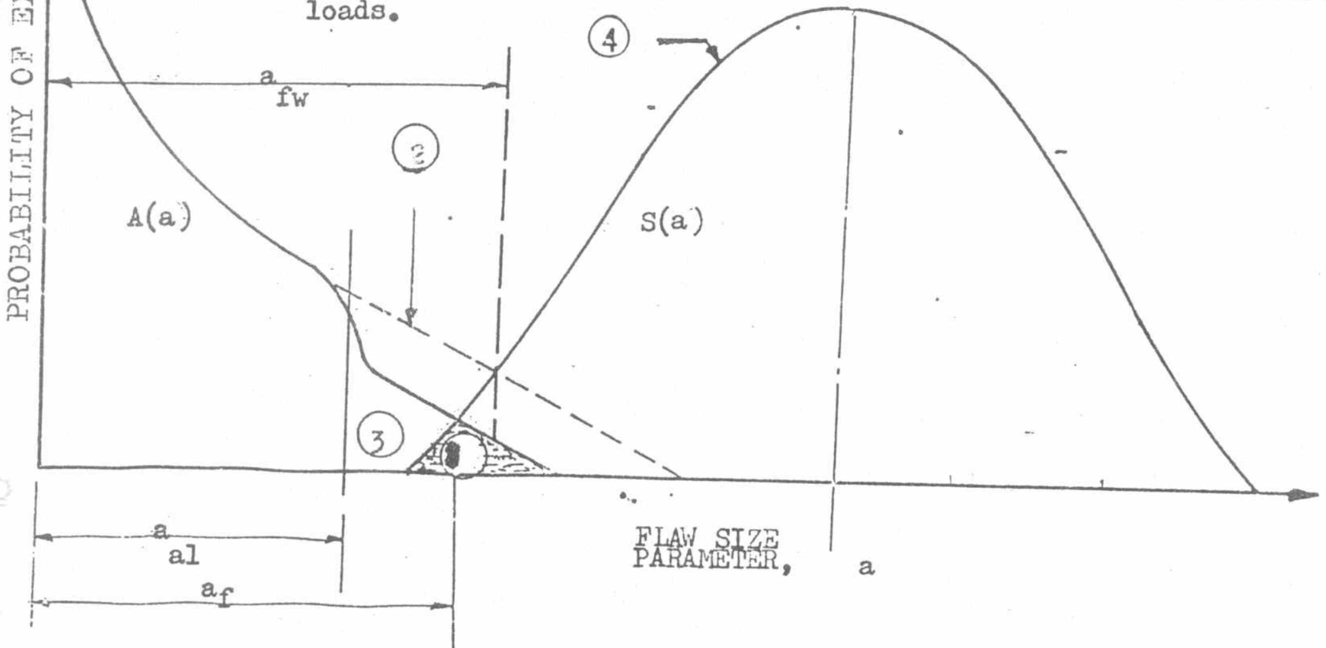


Fig. 4: RELIABILITY MODEL . (DEVELOPED FROM REF [29])

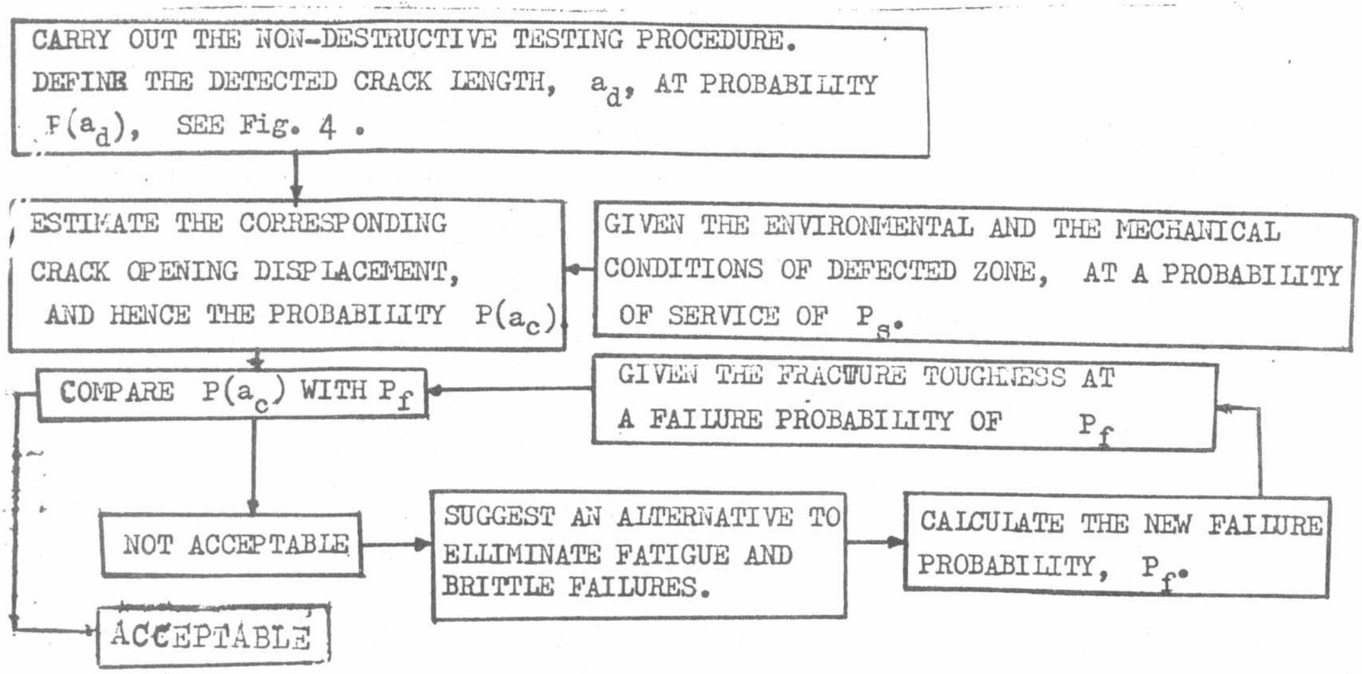


Fig. 5
FLOW DIAGRAM OF ACCEPTANCE CRITERIA OF A WELDED DEFECT, [29] .