Mar. 2011, Volume 5, No. 3 (Serial No. 40), pp. 265-272
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

Performance of Steel Structures under Fatigue Cyclic Loading

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Abstract: A component or structure, which is designed to carry a single monotonically increasing application of static load, may fracture and fail if the same load or even smaller load is applied cyclically a large number of times. For example a thin rod bent back and forth beyond yielding fails after a few cycles of such repeated bending. The fatigue failure is due to progressive propagation of flaws in steel under cyclic loading. This is partially enhanced by the stress concentration at the tip of such flaw or crack. The presence of a hole in a plate or simply the presence of a notch in the plate has created stress concentrations at the center points. These stress concentrations may occur in the material due to some discontinuities in the material itself. At the time of static failure, the average stress across the entire cross section would be the yield stress. However when the load is repeatedly applied or the load fluctuates between tension and compression, the center points experience a higher range of stress reversal than the applied average stress. These fluctuations involving higher stress ranges, cause minute cracks at these points, which open up progressively and spread with each application of the cyclic load and ultimately lead to rupture. Fatigue failure can be defined as the number of cycles and hence time taken to reach a pre-defined or a threshold failure criterion. Low cycle fatigue could be classified as the failures occurring in few cycles to a few tens of thousands of cycles, normally under high stress/ strain ranges. High cycle fatigue requires about several millions of cycles to initiate a failure. The type of cyclic stresses applied on structural systems and the terminologies used in fatigue resistant design are illustrated in this paper. The common form of presentation of fatigue data is by using the S-N curve, where the total cyclic stress (S) is plotted against the number of cycles to failure (N) in logarithmic scale. The point at which the S-N curve flattens off is called the "endurance limit". To carry out fatigue life predictions, a linear fatigue damage model is used in conjunction with the relevant S-N curve.

Key words: Fatigue, cyclic loading, S- N curve.

1. Introduction

Examples of structures, prone to fatigue failure, are bridges, cranes, offshore structures and slender towers, etc., which are subjected to cyclic loading.

The fatigue failure is due to progressive propagation of flaws in steel under cyclic loading. This is partially enhanced by the stress concentration at the tip of such flaw or crack.

The characteristic of fatigue are:

- The process starts with dislocation movements, eventually forming persistent slip bands that nucleate short cracks.
- Fatigue is a stochastic process, often showing considerable scatter even in controlled environments.
- The greater the applied stress range, the shorter the life.
- Fatigue life scatter tends to increase for longer fatigue lives.
- Damage is cumulative. Materials do not recover when rested.
- Fatigue life is influenced by a variety of factors, such as temperature, surface finish, presence of oxidizing or inert chemicals, residual stresses, contact (fretting), etc.
- Some materials (e.g., some steel and titanium alloys) exhibit a theoretical fatigue limit below which continued loading does not lead to failure.
- In recent years, researchers (see, for example, the work of Bathias, Murakami, and Stanzl-Tschegg) [1]

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have found that failures occur below the theoretical fatigue limit at very high fatigue lives (10^9 to 10^{10} cycles). An ultrasonic resonance technique is used in these experiments with frequencies around 10-20 kHz.

• High cycle fatigue strength (about 10^3 to 10^8 cycles) can be described by stress-based parameters. A load-controlled servo-hydraulic test rig is commonly used in these tests, with frequencies of around 20-50 Hz. Other sorts of machines like resonant magnetic machines can also be used, achieving frequencies up to 250 Hz.

• Low cycle fatigue (typically less than 10^3 cycles) is associated with widespread plasticity; Thus, a strain-based parameter should be used for fatigue life prediction. Testing is conducted with constant strain amplitudes at 1-5 Hz. [1, 9].

As we can see from Fig. 1, the presence of a hole in a plate or simply the presence of a notch in the plate has created stress concentrations at the points “m” and “n” as shown in Figs. 1 and 2. The stress at these points could be three or more times the average applied stress. These stress concentrations may occur in the material due to some discontinuities in the material itself. These stress concentrations are not serious when a ductile material like steel is subjected to a static load, as the stresses redistribute themselves to other adjacent elements within the structure.

At the time of static failure, the average stress across the entire cross section would be the yield stress

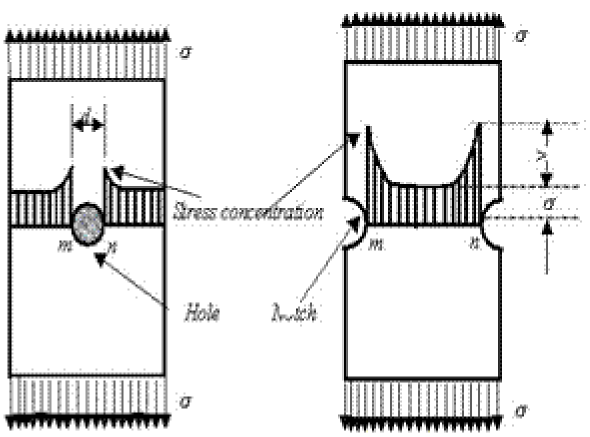

Fig. 1 Stress concentrations in the presence of notches and holes.

as shown in Fig. 2. However when the load is repeatedly applied or the load fluctuates between tension and compression, the points m, n experience a higher range of stress reversal than the applied average stress. These fluctuations involving higher stress ranges, cause minute cracks at these points, which open up progressively and spread with each application of the cyclic load and ultimately lead to rupture.

2. Fatigue Failure

The fatigue failure occurs after four different stages, namely:

(1) Crack initiation at points of stress concentration;

(2) Crack growth;

(3) Crack propagation;

(4) Final rupture.

The development of fatigue crack growth and the various stages mentioned above are symbolically represented in Fig. 3. Fatigue failure can be defined as the number of cycles and hence time taken to reach a pre-defined or a threshold failure criterion.

Fatigue failures are classified into two categories namely the high cycle and low cycle fatigue failures, depending upon the number of cycles necessary to create rupture. Low cycle fatigue could be classified as the failures occurring in few cycles to a few tens of thousands of cycles, normally under high stress/strain ranges [7, 8]. High cycle fatigue requires about several millions of cycles to initiate a failure. The type of cyclic stresses applied on structural systems and the terminologies used in fatigue resistant design are illustrated in Fig. 4.

$$S_{\max} = \frac{2S_{-1}S_{ult}}{S_{ult} + S_{-1} - K\left(S_{ult} - S_{-1}\right)} \quad (1)$$

Where :

S_{max} = Maximum Stress

S_{ult} = Ultimate Stress

K = Stress Intensity Factor

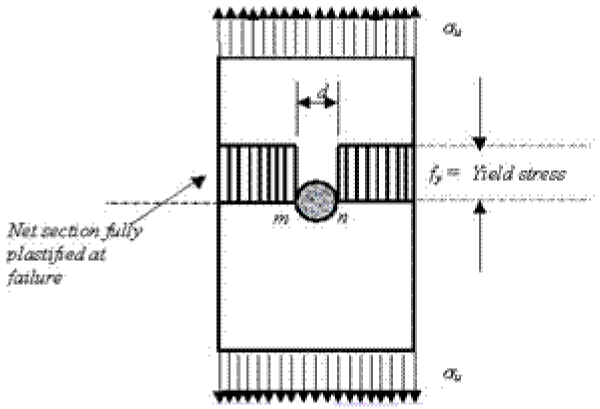

Fig. 2 Stress pattern at the point of static failure.

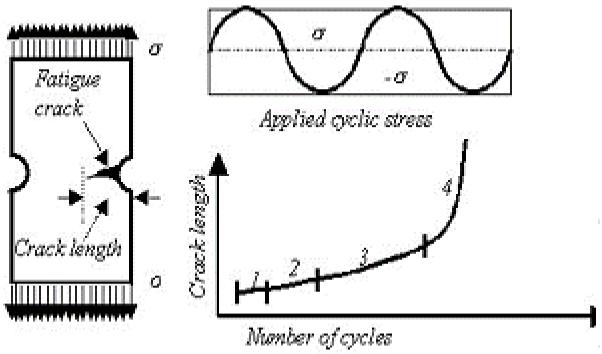

Fig. 3 Crack growth and fatigue failure under cyclic load.

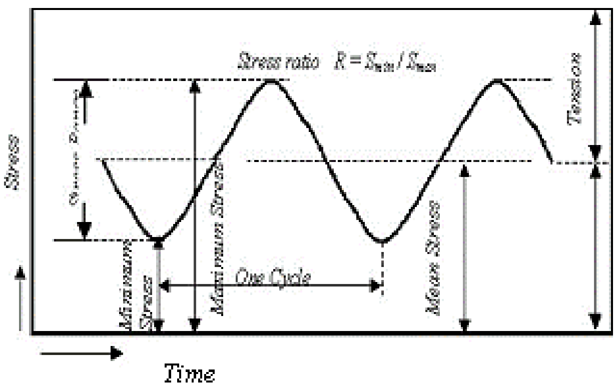

Fig. 4 Terminology used in fatigue resistant design of structural steel work.

3. S-N Curve and Fatigue Resistance Design

The common form of presentation of fatigue data is by using the S-N curve, where the total cyclic stress (S) is plotted against the number of cycles to failure (N) in logarithmic scale. A typical S-N curve is shown in Fig. 5. It is seen from Fig. 5 that the fatigue life reduces with respect to increase in stress range and at a limiting value of stress, the curve flattens off. The point at which the S-N curve flattens off is called the "endurance limit". To carry out fatigue life predictions, a linear fatigue damage model is used in conjunction with the relevant S-N curve. One such fatigue damage model is that postulated by Wohler as shown in Fig.5. The relation between stress and the number of cycles for failure could be written as:

$$\log N = \log C - m \cdot \log S \qquad (2)$$

where "N" is the number of cycles to failure, "C" is the constant dependant on detailing category, "S" is the applied constant amplitude stress range and "m" is the slope of the S-N curve. For the purpose of design it is more convenient to have the maximum and minimum stresses for a given life as the main parameters. For this reason the modified Goodman diagram, as shown in Fig. 5, is mostly used. The maximum stresses are plotted in the vertical ordinate and minimum stresses as abscissa. The line OA represents alternating cycle (R = -1), line OB represents pulsating cycle (R = 0) and OC the static load (R = 1). Different curves for different values of fatigue life "N" can be drawn through point "C" representing the fatigue strength for various numbers of cycles. The vertical distance between any point on the "N" curve and the 450 line OC through the origin represents the stress range. As discussed earlier, the stress range is the important parameter in the fatigue resistant design. Higher the stress range a component is subjected to, lower would be its fatigue life and lower the stress range, higher would be the fatigue life.

It becomes very important to avoid any local structural discontinuities and notches by good design and this is the most effective means of increasing fatigue life. Where a structure is subjected to fatigue, it is important that welded joints are considered carefully. Indeed, weld defects and poor weld details are the major contributors of fatigue failures. The fatigue performance of a joint can be enhanced by the use of techniques such as proper weld geometry, improvements in welding methods and better weld quality control using non-destructive testing (NDT) methods.

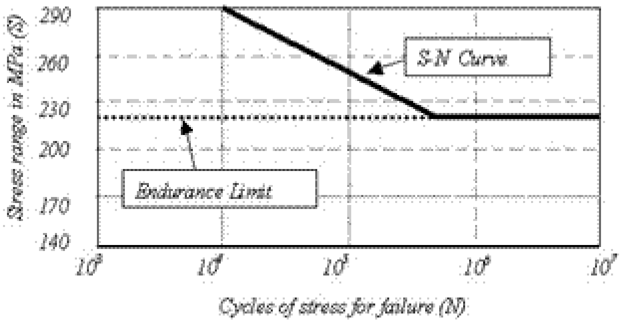

Fig. 5 S-N diagram for fatigue life assessment for steel material.

The following general points are important for the design of a welded structure with respect of fatigue strength: (1) use butt welds instead of fillet welds; (2) use double sided welds instead of single sided fillet welds; (3) pay attention to the detailing which may cause stress concentration and (4) in very important details subjected to high cyclic stresses use any non-destructive testing (NDT) method to ensure defect free details. From the point of view of fatigue design, the codes of practice classify various structural joints and details depending upon their vulnerability to fatigue cracks [2].

Each categories denoted by a number which corresponds to the stress for 5×10^6, classifies the detailing in the structural steel work in to several categories depending upon their vulnerability to stress concentrations. It provides S-N curves for all the categories. Using these curves the allowable stress (S) for a given life time (N) may be obtained. The accuracy of any fatigue life calculation is highly dependent on a good understanding of the expected loading sequence during the whole life of a structure. Once a global load pattern has been developed, then a more detailed inspection of particular area of a structure where the effects of loading may be more important called the "hot spot stresses" which are basically the areas of stress concentrations.

4. Fatigue Life

4.1 Cyclic Loading Life Fatigue Considerations

A component is stressed to some extent in its operating life. In all loading scenarios it is desirable to design the component to minimize stress concentrations and maximum the strength of the component material using good design practices [3].

4.1.1 Static Loading

If the component is stressed to a constant stress level for its operating life then fatigue loading design is not appropriate and for ductile materials the stress concentration factors are not important. If the component is brittle, e.g., Cast Iron, then the stress concentration factors need to be considered in the design process [5].

Design using the material yield strength and ultimate strength using the appropriate strength formulae and Factors of Safety can be completed.

4.1.2 Low Life Loading-Stress Cycles < 10^3 Stress Cycles over the Design Life

This condition is approached in a similar manner to the static loading scenario. There is a need to review the loading with respect to the material fatigue properties.

Approximate values for low life fatigue strength values for steel are provided below

- Bending $S'_l = 0.9\ S_u$
- Axial Loading $S'_l = 0.75\ S_u$
- Axial Loading $S'_l = 0.72\ S_u$

4.1.3 Finite Life Loading-Stress Cycles 10^3 to 10^6 Stress Cycles over Design Lifetime

Use S-N (Wohler) curve for relevant material and determine the relevant fatigue stress level at the relevant design life.

If this information is not available then an estimate of the fatigue strength S'_f can be made if the endurance limit and the low life strength values are available.

The fatigue modifying factors must be considered and the stress concentration factors should also be considered. If the cyclic stress level at different values over the operating lifetime then it may be appropriate to use the Palmgren-Miner rule see below.

4.1.4 Infinite Life Loading-Stress Cycles >10^6 Stress Cycles Design Lifetime

For ferrous metals and titanium alloys the endurance limit may be used S'_n. For non ferrous the fatigue strength limit S'_n may be used, with care, as a design material strength (assuming the n-cycles used is similar compared to the projected life).

The S'_n value to be modified by the appropriate fatigue modifying factors and the design should apply appropriate stress concentration values and factors of safety.

4.2 Palmgren-Miner

In actual service, parts are seldom stressed repeatedly at only one stress level and, hence, the problem arises as to the cumulative damage effect of operations at various levels of stress reversal. Consequently, the linear cumulative damage rule or the Palmgren-Miner rule has come into common usage. It assumes that the total life of a part may be estimated by merely adding up the percentage of life consumed by each stress cycle.

Thus, if a specimen, stressed at σ_1, has a life of N_1 cycles, the damage after n_1 cycles at σ_1 will be n_1/N_1 of the total damage, D, at failure. Similarly, for a two stress level test, where the lives at σ_1 and σ_2 are, respectively, N_1 and N_2, the corresponding damages, per cycle, being D/N_1 and D/N_2 the total damage at failure becomes: $D = D \cdot n_1/N_1 + D \cdot n_2/N_2$ or $1 = n_1/N_1 + n_2/N_2$ where n_1 and n_2 are the total number of cycles at σ_1 and σ_2, respectively.

For a multi-level test, Palmgren - Miner rule states

Failure if:

$$n_1/N_1 + n_2/N_2 + n_3/N_3 ...... > 1 \quad (3)$$

Example:

A component is designed for

- a stress of 360 MPa for 8,000 cycles. Life N_1 from S_N curve = 20,000 cycles
- a stress of 340 MPa for 10,000 cycles. Life N_2 from S_N curve = 40,000 cycles
- a stress of 280 MPa for 40,000 cycles. Life N_3 from S_N curve = 200,000 cycles

8,000/20,000+10,000/40,000+40,000/200,000 = 0.8

(This is less than 1).

The part will probably not fail in fatigue [4].

5. Results and Discussion

Historically, most attention has focused on situations that require more than 10^4 cycles to failure where stress is low and deformation primarily elastic.

In high-cycle fatigue situations, materials performance is commonly characterised by an S-N curve, as shown in Fig. 6, also known as a Wöhler curve. This is a graph of the magnitude of a cyclical stress (S) against the logarithmic scale of cycles to failure (N).

S-N curves are derived from tests on samples of the material to be characterized (often called coupons) where a regular sinusoidal stress is applied by a testing machine which also counts the number of cycles to failure. This process is sometimes known as coupon testing. Each coupon test generates a point on the plot though in some cases there is a runout where the time to failure exceeds that available for the test (see censoring). Analysis of fatigue data requires techniques from statistics, especially survival analysis and linear regression.

5.1 Probabilistic Nature of Fatigue

As coupons sampled from a homogeneous frame will manifest variation in their number of cycles to failure, the S-N curve should more properly be an S-N-P curve capturing the probability of failure after a given number of cycles of a certain stress. Probability distributions that are common in data analysis and in design against fatigue include the lognormal distribution, extreme value distribution, Birnbaum-Saunders distribution, and Weibull distribution.

$$\Delta = \sum_{i=1}^{k} \frac{n_i}{N_1} \quad (4)$$

Where:

n_i = number of cyclic loading in S_i;

N_i = number of cyclic loading for failure;

Δ = cumulative damage.

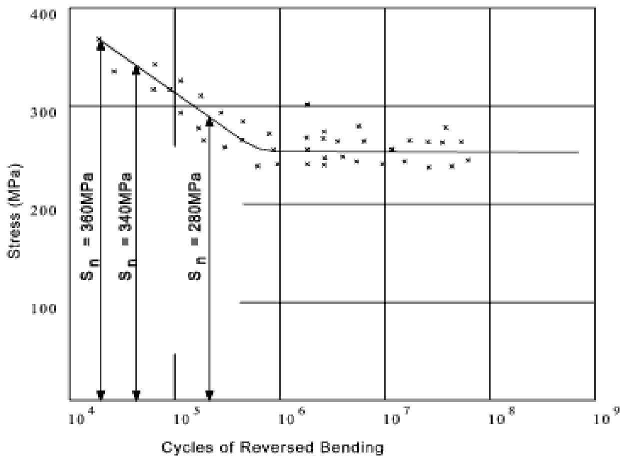

Fig. 6 S-N diagram example.

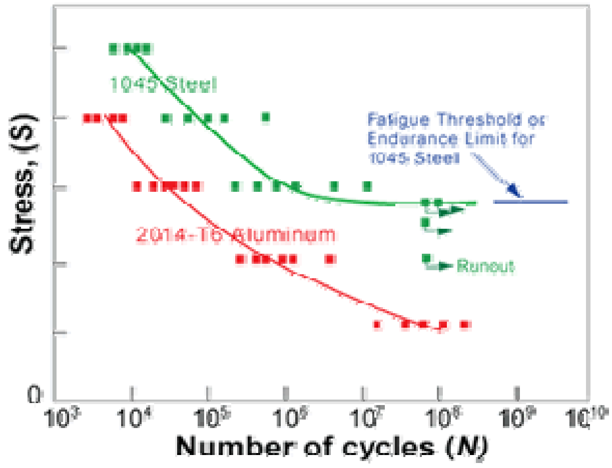

Fig. 7 S-N curve for brittle material.

5.2 Complex Loadings

5.2.1 Spectrum Loading

In practice, a mechanical part is exposed to a complex, often random, sequence of loads, large and small. In order to assess the safe life of such a part:

(1) Reduce the complex loading to a series of simple cyclic loadings using a technique such as rainflow analysis;

(2) Create an histogram of cyclic stress from the rainflow analysis;

(3) For each stress level, calculate the degree of cumulative damage incurred from the S-N curve as shown in Fig.7;

(4) Combine the individual contributions using an algorithm such as Miner's rule.

5.2.2 Miner's Rule

In 1945, M. A. Miner popularised a rule that had first been proposed by A. Palmgren in 1924 [6] . The rule, variously called Miner's rule or the Palmgren-Miner linear damage hypothesis, states that where there are k different stress magnitudes in a spectrum, S_i $(1 \leq i \leq k)$, each contributing $n_i(S_i)$ cycles, then if $N_i(S_i)$ is the number of cycles to failure of a constant stress reversal S_i, failure occurs when:

C is experimentally found to be between 0.7 and 2.2. Usually for design purposes, C is assumed to be 1.

This can be thought of as assessing what proportion of life is consumed by stress reversal at each magnitude then forming a linear combination of their aggregate.

Though Miner's rule is a useful approximation in many circumstances, it has two major limitations:

(1) It fails to recognize the probabilistic nature of fatigue and there is no simple way to relate life predicted by the rule with the characteristics of a probability distribution.

(2) There is sometimes an effect in the order in which the reversals occur. In some circumstances, cycles of low stress followed by high stress cause more damage than would be predicted by the rule. It does not consider the effect of overload or high stress which may result in a compressive residual stress. High stress followed by low stress may have less damage due to the presence of compressive residual stress.

5.2.3 Paris's Relationship

Anderson, Gomez and Paris derived relationships for the stage II crack growth with cycles N, in terms of the cyclical component ΔK of the Stress Intensity Factor K where a is the crack length and m is typically in the range 3 to 5 (for metals).

This relationship was later modified [6] to make better allowance for the mean stress, by introducing a factor depending on (1-R) where R = min. stress/max stress, in the denominator.

6. Low-Cycle Fatigue

Where the stress is high enough for plastic deformation to occur, the account in terms of stress is less useful and the strain in the material offers a simpler description. Low-cycle fatigue is usually characterized by the *Coffin-Manson relation* [6]:

where:

- $\Delta\varepsilon_p /2$ is the plastic strain amplitude;
- ε_f' is an empirical constant known as the *fatigue ductility coefficient*, the failure strain for a single reversal;
- 2N is the number of reversals to failure (N cycles);
- *c* is an empirical constant known as the fatigue ductility exponent, commonly ranging from -0.5 to -0.7 for metals.

7. Fatigue and Fracture Mechanics

The account above is purely phenomenological and, though it allows life prediction and design assurance, it does not enable life improvement or design optimization. For the latter purposes, an exposition of the causes and processes of fatigue is necessary. Such an explanation is given by fracture mechanics in four stages.

(1) Crack nucleation;
(2) Stage I crack-growth;
(3) Stage II crack-growth;
(4) Ultimate ductile failure.

7.1 Factors that Affect Fatigue-Life

- Cyclic stress state. Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or out-of-phase shear stress, and load sequence.
- Geometry. Notches and variation in cross section throughout a part lead to stress concentrations where fatigue cracks initiate.
- Surface quality. Surface roughness cause microscopic stress concentrations that lower the fatigue strength. Compressive residual stresses can be introduced in the surface by, e.g., shot peening to increase fatigue life. Such techniques for producing surface stress are often referred to as peening, whatever the mechanism used to produce the stress. Laser peening and ultrasonic impact treatment can also produce this surface compressive stress and can increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue.
- Material type. Fatigue life, as well as the behavior during cyclic loading, varies widely for different materials: e.g., composites and polymers differ markedly from metals.
- Residual stresses. Welding, cutting, casting, and other manufacturing processes involving heat or deformation can produce high levels of tensile residual stress, which decreases the fatigue strength.
- Size and distribution of internal defects. Casting defects such as gas porosity, non-metallic inclusions and shrinkage voids can significantly reduce fatigue strength.
- Direction of loading. For non-isotropic materials, fatigue strength depends on the direction of the principal stress.
- Grain size. For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse grained alloy.
- Environment. Environmental conditions can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Corrosion fatigue is a problem encountered in many aggressive environments.
- Temperature. Higher temperatures generally decrease fatigue strength.

7.2 Designs against Fatigue

Dependable design against fatigue-failure requires thorough education and supervised experience in structural engineering, mechanical engineering, or materials science. There are three principal approaches to life assurance for mechanical parts that display increasing degrees of sophistication:

(1) Design to keep stress below threshold of fatigue limit (infinite lifetime concept);

(2) Design (conservatively) for a fixed life after which the user is instructed to replace the part with a new one (a so-called lifted part, finite lifetime concept, or "safe-life" design practice);

(3) Instruct the user to inspect the part periodically for cracks and to replace the part once a crack exceeds a critical length. This approach usually uses the technologies of nondestructive testing and requires an accurate prediction of the rate of crack-growth between inspections. This is often referred to as damage tolerant design or "retirement-for-cause" [10].

7.3 Stopping Fatigue

Fatigue cracks that have begun to propagate can sometimes be stopped by drilling holes, called drill stops, in the path of the fatigue crack. [9] This is not recommended as a general practice because the hole represents a stress concentration factor which depends on the size of the hole and geometry. There is thus the possibility of a new crack starting in the side of the hole. It is always far better to replace the cracked part entirely. Several disasters have been caused by botched repairs to cracked structures.

8. Conclusions

Regarding to cyclic loading, the multi-crack model should be used with care if it is used for analysis of structures under cyclic loading as the damping and unloading stiffness have been overestimated. The result of the plastic-damage-contact model, Palmgren-Miner, is generally in good agreement with experimental results of the structural performance under cyclic loading. It is because the model takes into account most of effects of fatigue under cyclic loading. However, as the yield load at each cycle is slightly too high compared with experiment, slight modifications to the material properties will be checked.

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