

Study of Fatigue and Life Assessment of Steel Structures: IS 800:2007 Provision

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Abstract: Fatigue failures of steel structures have caused catastrophic failures, no such fatigue failure has been reported for concrete structures, although there have been speculations in some cases whether the failure might be due to fatigue. In the design and detailing of steel structures, details that might be prone to cracking should be minimized, or avoided if possible. The structures should be inspected for cracks, both during fabrication to limit the size of initial flaws and also during service to ascertain any crack growth. However, it is inevitable that cracks or crack-like discontinuities will be present in fabricated steel elements. Thus, the engineer is responsible to consider the consequences of potential fatigue and subsequent brittle fracture. Fatigue is the phenomenon of decrease of resistance of the material to repeated loading and failure take place at the value of the stresses well below the ultimate tensile strength of the material. Fatigue was incorporated into design criteria towards the end of the nineteenth century and has been extensively studied since then specially for mechanical parts. The fatigue behaviour of a fabricated steel structure is controlled by the presence of pre-existing cracks or crack-like discontinuities, which most often occur at welded connections or other areas of stress concentrations.

Fatigue failure may occur in many different forms: *mechanical fatigue*, when the components are under only fluctuating stress or strain; *creep fatigue*, when the components are under cyclic loading at high temperature; *thermo mechanical fatigue*, when both mechanical loading and temperature are cyclic; *corrosion fatigue*, when the components are under cyclic loading in the presence of a chemically aggressive environment



Fig 1 Typical striations around sample due to welds

Key words : Crack Propagation, Fatigue Fracture, S-N Curve

INTRODUCTION

Fatigue in metals is the process of initiation and growth of cracks under the action of repetitive tensile loads. If crack growth is allowed to go on long enough, failure of the member can result when the uncracked cross-section is sufficiently reduced such that the member can no longer carry the internal forces for the crack extends in an unstable mode. The fatigue process can take place at stress levels that are substantially less than those associated with failure under static loading conditions. The usual condition that produces fatigue cracking is the application of a large number of load cycles.

Consequently, the types of civil engineering applications that are susceptible to fatigue cracking include structures such as bridges, crane support structures, gantry girders, stacks and masts, and offshore structures, tower-like (open) structures (subject to wind oscillations).

Fatigue failures may be classified as high-cycle and low-cycle fatigue failures. Under high cycle fatigue, the material deforms primarily elastically, and the number of cycles for failure, or the failure time, is characterized in terms of the stress range. Low-cycle fatigue can be characterized by the presence of macroscopic cyclic plastic strains as evidenced by a stress-strain hysteresis loop. Depending on the material strength and ductility, the upper limit of the low-cycle fatigue regime may be from 100 to 100,000 cycles or more. For common ductile structural materials, the low-cycle fatigue regime is generally limited to less than 50,000 cycles

The major loads that a building is subjected to are dead, live, wind, and earthquake loads. Dead and live loads are always present. The occurrence of cyclic stresses in buildings is usually caused by machinery and the induced cyclic stresses are typically low. Steel can withstand an infinite number of load reversals at low stresses. Hence, in buildings, fatigue is not considered in the design of members and structures supporting large rotating equipment. Crack growth in metals requires two existing conditions: existing flaws and tensile stresses. This crack growth can be delineated into three

distinct regimes: initiation, steady-state propagation and unstable fracture.

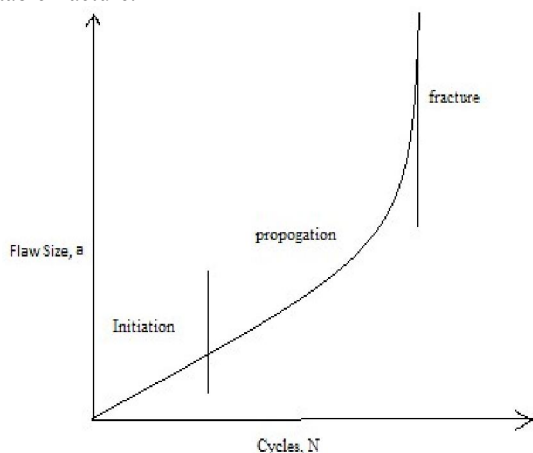


Fig 2 Graph for Regimes of Cracks

The Fig-2 shows a graph identifying the regimes of crack growth in metals. The horizontal axis is the number of load cycles, N , the vertical axis is the flaw size, a . the graph shows that as the number of cycles increase, the flaw size increases, and increases more rapidly as the number of cycles increases until fracture occurs. There are three regimes shown as the number of cycles increases: crack initiation, crack growth, and then fracture

LITERATURE REVIEW

Nawir Rasidi, Agoes Soehardjono MD and Sri Murni Dewi , Mar. 2011 in their paper stated that 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 centre 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.

Henning Agerskov, 2000 in their paper have carried out fatigue tests and the fracture mechanics analyses using load histories. Both the fracture mechanics analysis and the fatigue test results indicate that Miner's rule, which is normally used in the design against fatigue in steel structures, may give results, which are unconservative.

M. Al-Emrani & R. Kliger, 2009 in their paper have concluded after investigation of more than 100 fatigue damage cases reported for steel and composite bridges. It was found that more than 90% of all reported damage cases are of the deformation-induced type and are generated by some kind of unintentional or otherwise overlooked interaction between different load-carrying members or systems in the bridge. Poor detailing, with unstiffened gaps and abrupt changes in stiffness at the connections between different members, also contributed to fatigue cracking in most details.

Mohammad Shah Alam, 2005 in his dissertation have concluded that weld imperfections significantly reduce the fatigue crack propagation life and fatigue strength of welded join Improvement of weld geometry decreases the stress

concentration and increases the fatigue strength. At low range of stress intensity factor the fatigue life increases rapidly and its trend is toward infinity. At low stress level, the accumulation of fatigue crack growth is very low and the fatigue life increases toward infinity.

L.N.Ojha and R. K. Dube in their paper *Fatigue: A disastrous failure of welded structures* have reviewed a general history of failure caused due to fatigue, its development, causes and remedial measures. A study of fatigue failures reveals that not all the failures are caused by inappropriate design. In majority of the cases the failure could be attributed to geometric factors and imperfections in the structure. Obviously, then attention to design details alone is not sufficient to ensure against failure. Careful workmanship is essential in welding. It has become increasingly evident that defects introduced through poor workmanship or by accident must bedetected by deligent and well trained inspectors prior to the time that the structure is put into service.

Phases in the fatigue process

The process of fatigue failure starts with dislocation movements, eventually forming persistent slip bands that nucleate short cracks. The essential conditions for fatigue failure are cyclic tensile loads, stress levels above a threshold value, and a flaw in the material.

The phases of fatigue, as illustrated by Figure 1, are:

1. Crack initiation
2. Crack growth
3. Crack propagation
4. Final rupture

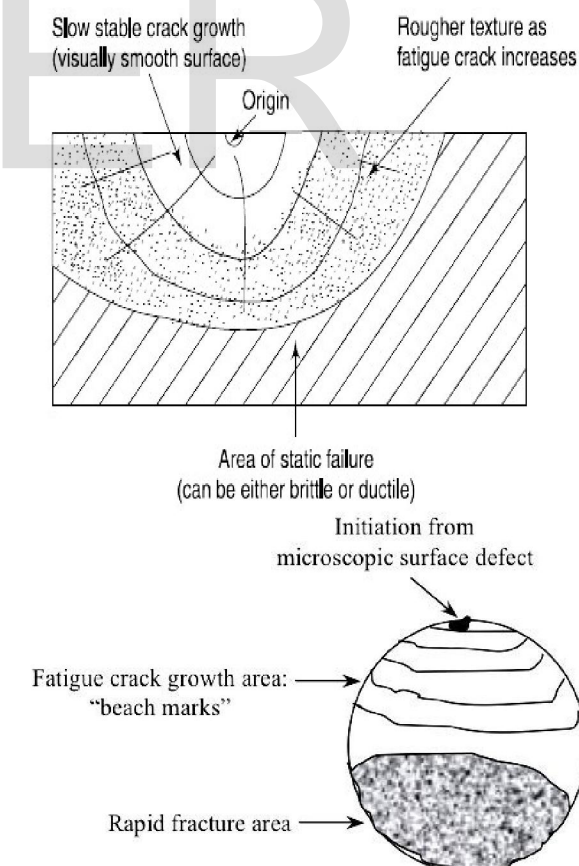


Fig 2 Initiation and propogation of crack



Fig 3 Component failed due to Fatigue Failure Example

Crack initiation and Growth

Areas of localized stress concentrations such as fillets, notches, key ways, bolt holes and even scratches or tool marks are potential zones for crack initiation. Cracks also generally originate from a geometrical discontinuity or metallurgical stress raiser like sites of inclusions. As a result of the local stress concentrations at these locations, the induced stress goes above the yield strength (in normal ductile materials) and cyclic plastic straining results due to cyclic variations in the stresses. On a macro scale the average value of the induced stress might still be below the yield strength of the material. During plastic straining slip occurs and (dislocation movements) results in gliding of planes one over the other. During the cyclic stressing, slip saturation results which makes further plastic deformation difficult. As a consequence, intrusion and extrusion occurs creating a notch like discontinuity in the material.

Crack propagation

- This further increases the stress levels and the process continues, propagating the cracks across the grains or along the grain boundaries, slowly increasing the crack size.
- As the size of the crack increases the cross sectional area resisting the applied stress decreases and reaches a threshold level at which it is insufficient to resist the applied stress.

Final fracture

- As the area becomes too insufficient to resist the induced stresses any further a sudden fracture results in the component.

FACTORS AFFECTING FATIGUE LIFE

- Material defects
- Surface roughness and surface treatments
- Imperfection in assembly or functionality requirements in design
- Size
- Loading types
- Harsh environments
- Damage in service
- Poor maintenance and improper repair.
- The number of cycles of loading to which the member is subjected to.
- The stress range at the location

Size Effect

The larger the component, the more initial imperfections within the component. Experiments done on carbon steel alloy found that the diameter of steel rod does affect the fatigue life when the rod is under axial (tension-compression) loading.

Surface Roughness

For many common types of loading, such as bending and torsion, the maximum stress occurs at the surface. Furthermore, the surface is exposed to harsh environments such as corrosion, or unexpected loads such as scratch and impact. In addition, experiments show that even the failure of axial loading usually begins at the surface. With all the evidences pointing to the surface, it is necessary to understand the effect of surface roughness and the treatments improving surface properties

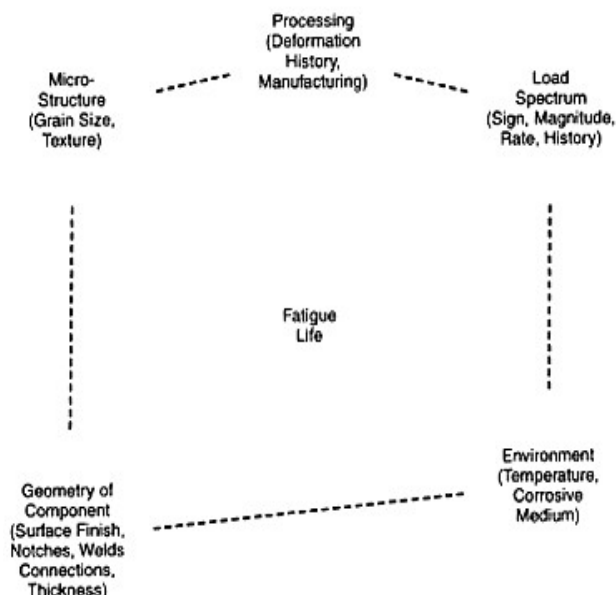


Fig 4- Factors Affecting fatigue life of component

DIFFERENT APPROACHES OF FATIGUE ANALYSIS

Wohler's experiments with axles during 1852–60 were the first known laboratory tests with the objective to derive and quantitatively describe the limits for fatigue.

The approaches for fatigue analysis can be classified into

- (1) The stress method,
- (2) The strain method, and
- (3) The crack propagation method.

Stress and Strain Methods: These methods characterize the total fatigue life in terms of cyclic stress range or strain range. In these methods, the number of stress or strain cycles to induce fatigue failure in an initially uncracked or smooth surfaced laboratory specimen is estimated under controlled cyclic stress or strain. The resulting fatigue life includes the fatigue crack initiation life to initiate a dominant crack and a propagation of this crack until catastrophic failure. Normally, the fatigue initiation life is about 90% of the total life due to the smooth surface of the specimen. Under a high-cycle ($> 10^2$ to 10^4) low-stress fatigue situation, the material deforms primarily elastically and the failure time has traditionally been described in terms of stress range. However, stresses associated with low-cycle fatigue ($< 10^2$ to 10^4) are generally high enough to cause plastic deformation prior to failure. Under these circumstances, the fatigue life is described in terms of the strain range. The low-cycle approach to fatigue design has found particularly widespread use in ground vehicle industries.

Crack Propagation Method (Fracture mechanics approach): The basic principle of this method is that all engineering components are essentially flawed. The size of a pre-existing flaw is generally determined from non-destructive flaw detection techniques, such as visual, dye-penetrant, or x-ray techniques, or the ultrasonic, magnetic, or acoustic emission methods. The fatigue life is then defined as the number of cycles to propagate the initial crack size to a critical size. The choice of the critical size of cracks may be based on the fracture toughness of the material, the limit load for the

particular structural part, the allowable strain, or the permissible change in the compliance of the component. The prediction of fatigue life is mainly based on linear elastic *fracture mechanics*. The crack propagation method, which is a conservative approach to fatigue, has been widely used in fatigue-critical applications where catastrophic failures will result in the loss of human lives, such as aerospace and nuclear industries.

We will confine our attention to the stress method, which is followed by the IS: 800-2007.

The relation between stress and the number of cycles for failure could be written as

$$\log N = \log C - m \log S$$

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.

ANALYSIS PROCEDURES AND DESIGN PHILOSOPHY (IS 800-2007)

An improved design philosophy to make allowances for the shortcomings in the *Working Stress Method* was developed in the late 1970's and has been extensively incorporated in design standards and codes. The probability of operating conditions not reaching failure conditions forms the basis of *Limit State Method* (LSM).

Fatigue Limit State is important where distress to the structure by repeated loading is a possibility. Stress changes due to fluctuations in wind loading normally need not be considered. **Fatigue design shall be as per Section 13 of IS 800:2007.** When designing for fatigue, the load factor for action, γ_f , equal to unity shall be used for the load causing stress fluctuation and stress range.

S-N curves and fatigue resistant 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.

As per IS 800-2007

The values obtained from the standard S-N curve shall be modified by a capacity reduction factor p

$$\mu_t = (25/t_p)^{0.25} \leq 1.0$$

Fatigue Strength

The fatigue strength of the standard detail for the normal or shear fatigue stress range, not corrected for effects discussed in 13.2.1, is given below (see also Fig. 22 and Fig. 23):

a) Normal stress range

when $N_{sc} \leq 5 \times 10^6$

$$f_f = f_{fn} \sqrt[3]{5 \times 10^6 / N_{sc}}$$

When $5 \times 10^6 \leq N_{sc} \leq 10^8$

$$f_f = f_{fn} \sqrt[5]{5 \times 10^6 / N_{sc}}$$

Fatigue Assessment

The design fatigue strength for N_{sc} life cycles (f_f, τ_f) may be obtained from the standard fatigue strength for N_{sc} cycles

by multiplying with correction factor, μ_r for thickness and dividing by partial safety factor given in code

$$N_{sc} < 5 \times 10^6 \left(\frac{27/\gamma_{mft}}{\gamma_{fft} f} \right)^3$$

where

$\gamma_{mft}, \gamma_{fft}$ = Partial safety factors for strength and load, respectively, and

f = actual fatigue stress range for the detail.

NECESSITY FOR FATIGUE ASSESSMENT

a) Fatigue assessment is not normally required for building structures except as follows:

- 1) Members supporting lifting or rolling loads,
- 2) Member subjected to repeated stress cycles from vibrating machinery,

3) Members subjected to wind induced oscillations of a large number of cycles in life, and

4) Members subjected to crowd induced oscillations of a large number of cycles in life

USING S-N METHOD TO EVALUATE FATIGUE LIFE

Several $S-N$ methods are available for estimating the fatigue life of welded components: nominal stress method, structural hot spot stress method, notch stress method, notch stress intensity method, and notch strain method (Fricke 2003). Fatigue assessment according to the nominal stress method uses several $S-N$ curves together with detail classes of basic joints. This is the simplest and most Common method adopted for estimating the fatigue life of structural joints and elements.

The Eurocode 3-1993, Canadian code CAN/CSA-S.16.1, 2001, and the Indian code IS: 800 are based on this method.

The fatigue strength in IS: 800 is defined by a series of $\log f_f - \log N$ or $\log \tau_f - \log N$ curves, each applying to a typical detail category. Each category is designated by a number which represents the reference value f_m (normal fatigue stress range) at 2 million cycles, i.e., the number of stress cycles, $N_{sc} = 2 \times 10^6$. The values are rounded values. Detail types and their fatigue categories are provided in Table 26(a) to table 25 (d) of the code.

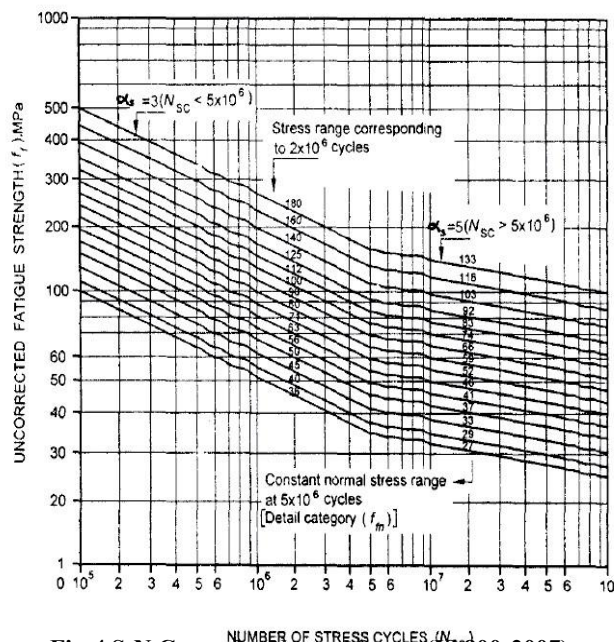


Fig-4 S-N Curve for Normal Stress (IS 800-2007)
FIG. 22 S-N CURVE FOR NORMAL STRESS

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