Fatigue Phenomenon in Materials

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Biography

Dr. Fahmida Gulshan (born in March, 1978, Rangpur, Bangladesh) obtained her Bachelor of Science in Metallurgical Engineering Degree from Bangladesh University of Engineering and Technology, Dhaka in 2003. She topped the list of the graduating students in her batch with a CGPA of 3.84 out of 4.00. During her undergraduate studies she achieved several scholarships like University Merit Award, Board Scholarship and the Dean's List scholarship. In 2003 she joined the Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka as a Lecturer. Then she obtained Master of Science in Materials and Metallurgical Engineering Degree from BUET, Dhaka in 2006. After that she received Monbukagakusho scholarship for doctorate program and obtained Ph.D. from Tokyo Institute of Technology, Japan in 2009. Now she is working as an Assistant Professor in the Department of Materials and Metallurgical Engineering, BUET, Dhaka.

Her areas of interest include industrial waste recycling, water treatment, welding and steel. She has published about 30 papers in reviewed journals and conference proceedings. She has also presented a number of technical papers in national and international conferences. She is continuing several research projects financed by Ministry of Science and Technology, Bangladesh. She is reviewer of International Journal of Material Science (IJMSCI). She has supervised two M Phil thesis and four more student registered for M Phil/MSc Engg. degrees of this university are now working under her supervision. She has also supervised several undergraduate theses.

She has visited Japan, India, Nepal, Malaysia, China and France for higher studies, to attend seminars and conferences and for traveling. Besides her professional career she also graduated from the prestigious music school CHAYYANOT in 1994 and enjoys singing.

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Abstract

Metal fatigue results from the progressive and localized structural damage that occurs when a material is subjected to cyclic loading and results in failure at stress levels which are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material. Fatigue considerations are important because the consequent failure is generally sudden and at a stress level much lower than the strength values determined for normal tensile tests. During the last few years there has been an intensification of interest in the fatigue performance of modern and sophisticated technological machines and structures like high speed aircrafts, nuclear vessels, space shuttles, launch vehicles, ships, submarines, pressure vessels, high speed trains steel reinforcement bars in concrete structures, etc which can be devastating in the event of their fatigue failure. In this paper the main parameters associated with fatigue have been reviewed.

Behaviour of Materials Under Load

The application of a force to an object is known as loading. Materials can be subjected to many different loading scenarios. The way a material is loaded greatly affects its mechanical properties and largely determines how, or if, a component will fail; and whether it will show warning signs before failure actually occurs.

A tensile test is a fundamental mechanical test where a carefully prepared specimen is loaded in a very controlled manner while measuring the applied load and the elongation of the specimen. The main product of a tensile test is a load versus elongation curve which is then converted into a stress versus strain curve. The stress and strain initially increase with a linear relationship. In ductile materials, at some point, the stress-strain curve deviates from the straight-line relationship and the material is said to react plastically to any further increase in load or stress. This stress required to produce a small amount of plastic deformation is known as yield strength. For most engineering design and specification applications, the yield strength is used. Sometimes a proof stress also called offset yield strength [the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specified strain (typically 0.2% for metals)] is used in lieu of yield stress.

The maximum engineering stress level reached in a tension test is known as UTS and represents the ability to withstand external forces without breaking. In brittle materials, the UTS is close to the elastic limit. In ductile materials, the UTS will be well outside of the elastic portion into the plastic portion of the stress-strain curve. The UTS value is not typically used in the design of components anyway. However, since the UTS is easy to determine and q uite reproducible, it is useful for the purposes of specifying a material and for quality control purpose.

Fatigue Failure

Behaviour of metal under cyclic load differs from that under monotonic load. Failures can and do occur in structures subjected to cyclic loading (e.g., bridges, aircraft and machine components). Such failures are known as fatigue failures. Large number of cycles are needed for failure by fatigue. The term fatigue is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. Fatigue is important inasmuch as it is the single largest cause of failure in metals estimated to comprise approximately 90% of all metallic failures; Furthermore it is catastrophic and insidious, occurring very suddenly and without warning. Fatigue manifests in the form of initiation or nucleation of a crack followed by its growth till the critical crack size of the parent metal under the operating load is reached leading to rupture. The crack advances continuously by very small amounts, its growth rate decided by the magnitude of load and geometry of the component. Also the nucleated crack may not grow at all or may propagate extremely slowly resulting in high fatigue life of the component if the applied stress is less than the metal fatigue limit.

Cyclic stresses:

The applied stress may be axial (tension-compression), flexural (bending), or torsional (twisting) in nature. In general, three different fluctuating stress–time modes are possible. One is represented schematically by a regular and sinusoidal time dependence in Figure 1a, wherein the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress (max) to a minimum compressive stress (σ_{min}) of equal magnitude; this is referred to as a reversed stress cycle.

Another type, termed repeated stress cycle, is illustrated in Fig. 1b; the maxima and minima are asymmetrical relative to the zero stress level. Finally, the stress level may vary randomly in amplitude and frequency, as exemplified in Fig. 1c. Also indicated in Fig. 1b are several parameters used to characterize the fluctuating stress cycle. The stress amplitude alternates about a mean stress m) defined as the average of the maximum and minimum stresses in the cycle, or

$\sigma_m = (\sigma_{max}+\sigma_{min})/2$

Furthermore, the range of stress is just the difference between and — namely,

$\sigma_r = \sigma_{max}-\sigma_{min}$

Stress amplitude is just one half of this range of stress, or

$\sigma_a = \sigma_r /2=(\sigma_{max}-\sigma_{min})/2$

Finally, the stress ratio R is just the ratio of minimum and maximum stress amplitudes:

$R =\sigma_{max} / \sigma_{min}$

By convention, tensile stresses are positive and compressive stresses are negative.

For example, for the reversed stress cycle, the value of R is -1.

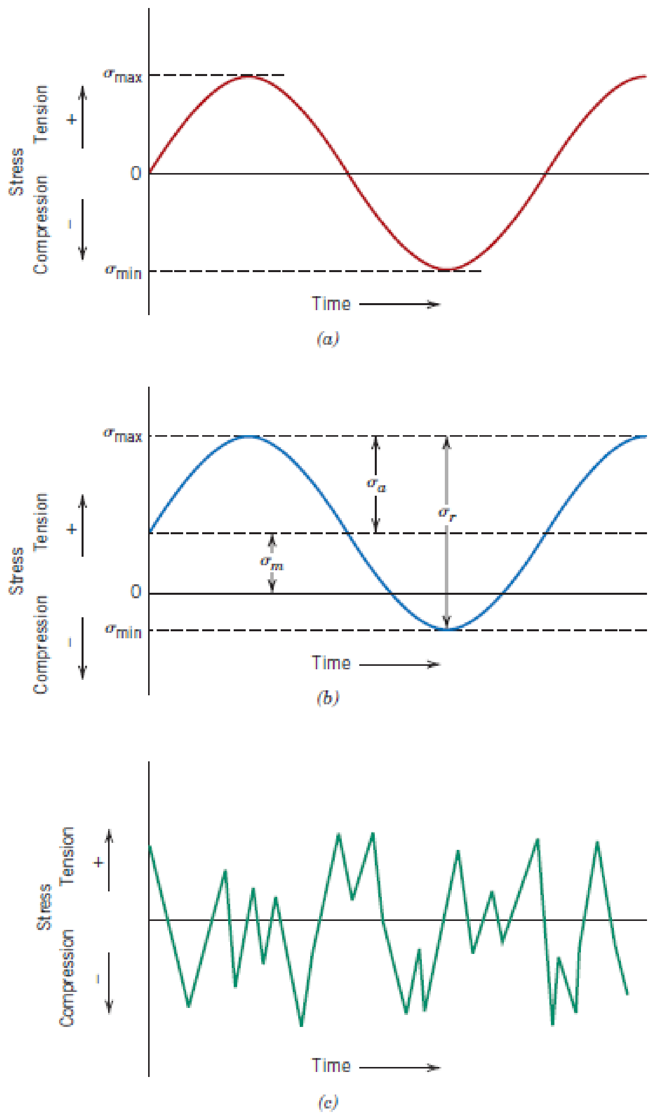


Fig.1: Variation of stress with time that accounts for fatigue failures (a) Reversed stress cycle, in which the stress alternates

from a maximum tensile stress to a maximum compressive stress of equal magnitude (b) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero stress level; mean stressm, range of stressr , and stress amplitude a are indicated (c) Random stress cycle

Fatigue testing:

As with other mechanical characteristics, the fatigue properties of materials can be determined from laboratory simulation tests. A test apparatus should be designed to duplicate as nearly as possible the service stress conditions (stress level, time frequency, stress pattern, etc.). A schematic diagram of a rotating-bending test

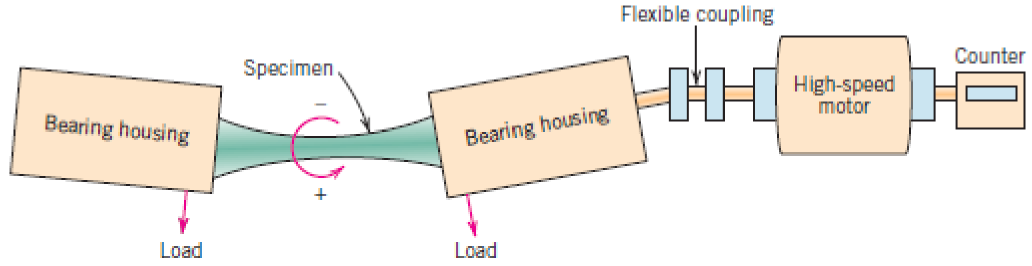


Fig.2: Schematic diagram of fatigue testing apparatus for making rotating bending tests.

apparatus, commonly used for fatigue testing, is shown in Fig. 2; the compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated. Tests are also frequently conducted using an alternating uniaxial tension-compression stress cycle.

A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude σ_{max}, usually on the order of two-thirds of the static tensile strength; the number of cycles to failure is counted. This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes. Data are plotted as stress S versus the logarithm of the number N of cycles to failure for each of the specimens. The values of S are normally taken as stress amplitudes; on occasion σ_{max} Or σ_{min} values may be used.

Two distinct types of S–N behavior are observed, which are represented schematically in Fig.3. As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure. For some ferrous (iron base) and titanium alloys, the S–N curve (Fig. 3a) becomes horizontal at higher N values; or there is a limiting stress level, called the fatigue limit (also sometimes the endurance limit), below which fatigue failure will not occur. This fatigue limit represents the largest value of fluctuating stress that will not cause failure for essentially an infinite number of cycles.

For many steels, fatigue limits range between 35% and 60% of the tensile strength. Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the S–N curve continues its downward trend at increasingly greater N values (Fig. 3b).Thus, fatigue will ultimately occur regardless of the magnitude of the stress. For these materials, the fatigue response is specified as fatigue strength, which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., cycles). The determination of fatigue strength is also demonstrated in Fig. 3b.

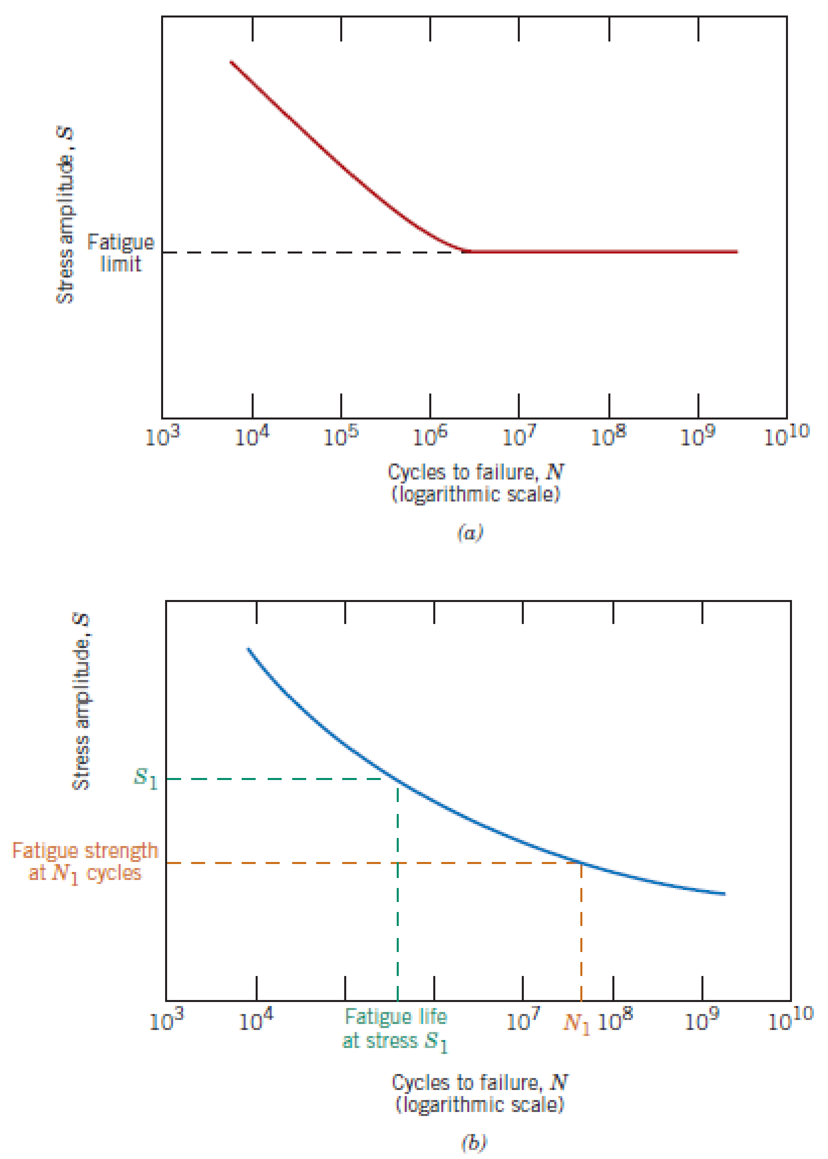


Fig.3. Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit (b) a material that does not display a fatigue limit.

Another important parameter that characterizes a material's fatigue behavior is fatigue life It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot (Fig.3b).

Unfortunately, there always exists considerable scatter in fatigue data—that is, a variation in the measured N value for a number of specimens tested at the same stress level. This variation may lead to significant design uncertainties when fatigue life and/or fatigue limit (or strength) are being considered. The scatter in results is a consequence of the fatigue sensitivity to a number of test and material parameters that are impossible to control precisely. These parameters include specimen fabrication and surface preparation, metallurgical variables, specimen alignment in the apparatus, mean stress, and test frequency.

Fatigue S–N curves similar to those shown in Fig. 3 represent "best fit" curves that have been drawn through average-value data points. It is a little unsettling to realize that approximately one-half of the specimens tested actually failed at stress levels lying nearly 25% below the curve (as determined on the basis of statistical treatments). Several statistical techniques have been developed to specify fatigue life and fatigue limit in terms of probabilities. One convenient way of representing data treated in this manner is with a series of constant probability curves.

The fatigue behaviors represented in Fig.3a and 3b may be classified into two domains. One is associated with relatively high loads that produce not only elastic strain but also some plastic strain during each cycle. Consequently, fatigue lives are relatively short; this domain is termed low-cycle fatigue and occurs at less than about to cycles. For lower stress levels wherein deformations are totally elastic, longer lives result. This is called high-cycle fatigue inasmuch as relatively large numbers of cycles are required to produce fatigue failure. High-cycle fatigue is associated with fatigue lives greater than about to cycles.

One recommended procedure for Fatigue testing of steel reinforcement:

Testing shall be carried out on ribbed steel reinforcing bars in the nominally straight condition. The stress range for the relevant bar size is given in Table 1.

Test specimen

The surface of the free length between the grips shall not be subjected to any surface treatment of any kind and the free length shall be at least 140 mm or 14d, whichever is the greater.

The straightness of the test specimen is critical for the fatigue test. To achieve satisfactory straightness, a production straightening machine may be used. The means of straightening the test specimen (manual, laboratory machine, production machine) shall be recorded in the test report.

Test equipment

The fatigue testing machine shall be calibrated according to ISO 7500-1:2004. The relative error of accuracy shall be at least ±1%. The testing machine shall be capable of maintaining the upper force, Fup, within ±2% of the specified value, and the force range, Fr, within ±4% of the specified value where the Fup and Fr can be determined as follows:

$F_{up} = \sigma_{max} \times A_n$

$Fr = 2\sigma_a \times A_n$

Where σ_{max} is the maximum stress in the axial load

$2\sigma_a$ is the stress range in the axial load

A_n is the nominal cross sectional area of the bar

Test procedure

The test specimen shall be gripped in the test equipment in such a way that the force is transmitted axially and free of any bending moment along the test specimen. The test shall be carried out under condition of stress ratio (σmin/σmax) of 0.2 and stress range as given in Table 1 and frequency of load cycles between 1 Hz and 200 Hz. The test frequency of load cycles shall be stable during the test and also during test series. The sine wave form shall be used. Testing shall be carried out under load control and stresses shall be calculated on the nominal cross-sectional area. There shall be no interruptions in the cyclic loading throughout the test. However, it is permissible to continue a test if it is accidentally interrupted. Any interruption shall be reported. The number of load cycles shall be counted inclusively from the first full load range cycle. The test shall be terminated upon failure of the test specimen before reaching the specified number of cycles, or on completion of the specified number of cycles without failure.

Table 1: Fatigue stress ranges for nominal bar sizes

Bar size, *d* (mm)	Stress range, $2\sigma_a$ (MPa)
$d \leq 16$	200
$16 < d \leq 20$	185
$20 < d \leq 25$	170
$25 < d \leq 32$	160
$d > 32$	150

The steel reinforcing bars shall be deemed to comply with the Standard if five test specimens can endure 5 × 106 cycles of stress in the fatigue test.

If one of the five test specimens fails in the test, a further five test specimens from the test unit shall be tested. If one of these further test specimens fails the test, the batch shall be deemed not to comply with this Standard. If all five further test specimens endure 5 × 106 cycles of stress, then the batch shall be deemed to comply with this Standard.

In the case of any failure, the test shall be considered invalid if it is initiated from a defect unique to the test piece or in the region within 2d of the testing machine grips (where d is the nominal steel reinforcing bar diameter); in this case a further single test shall be carried out.

Nucleation and propagation of cracks constitute major fatigue mechanisms. Initiation of fatigue crack at smooth polished surface under ambient conditions may consume nearly 90% of applied cycles while crack propagation may require only remaining 10% cycles. Distribution of cycles changes in defective specimens with environment also playing a major role.

Initiation of a new crack in smooth polished metals under cyclic load is caused by irreversible dislocation movement leading to intrusions and extrusions. (A dislocation is the flaw in the lattice of the metal which causes slip to occur along favorable oriented crystallographic planes upon application of stress to the lattice). These dislocations agglomerate into bundles almost perpendicular to the active Burger's vector. (Burger's vector represents magnitude and direction of slip). Strain localization occurs when dislocation pattern in a few veins or bundles becomes locally unstable at a critical stress or strain thereby leading to formation of thin lamellae of persistent slip bands or PSB's. The subsequent deformation is mainly concentrated in these slip bands as they increase and fill the entire volume of the crystal. If the PSB's are removed by electro-polishing, it will be found by retesting that they reform in the same area and become persistent. That is why the slip bands are also referred to as the persistent slip bands. They are very soft as compared to hard parent metal. Mechanism of formation of PSB's is different in different metals.

Fig. 4 shows a schematic of slip during monotonic and cyclic load. Under monotonic load, slip lines are formed in metal that are sharp and straight and are distributed evenly over each grain. Under high magnification, the individual lines appear as bands of parallel lines of various heights. On the other hand, the slip lines produced under cyclic load form in bands that do not necessarily extend right across a grain. New slip lines form beside old ones as the test proceeds. Although these bands grow wider and become more dense, there are areas between the bands where no slip takes place. Inhomogenity at the microscopic level, when the plastic strain in the PSB lamellae is at least an order of magnitude higher than the metal matrix, causes the crack to eventually form at the interface of PSB and the matrix. Also across the PSB-matrix interface, there is high strain gradient due to PSB's being softer in nature and the matrix being harder.

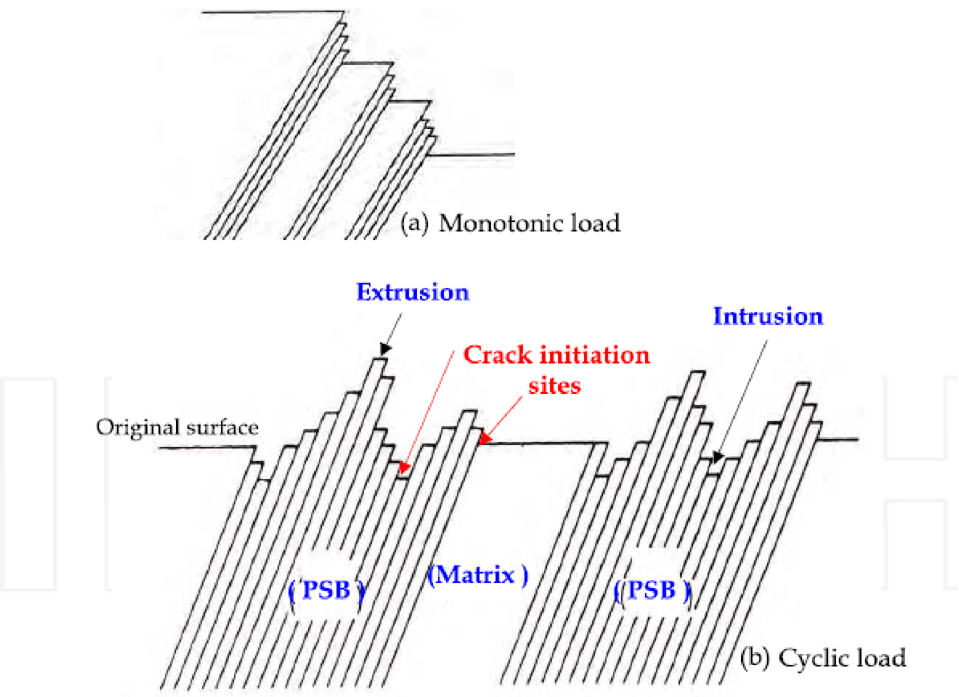


Fig. 4: Schematic of slip under (a) monotonic load and (b) cyclic load

The deformation compatibility requirement at the interface results in high shear stress along the interface leading to cracks. Crack initiation is aided by environmental effects also. Atmospheric oxygen diffuses into slip bands of PSB's thereby weakening them and accelerating initiation. On the other hand, crack initiation in an inert environment may be retarded by up to two orders of magnitude. Favorable crack initiation sites at micro-level can be stated as:- i) Slip steps between emerging extrusions of PSB's and the matrix ii) At micro notches near outer edges iii) At intrusion sites and iv) Grain boundaries in the case of high temperature and corrosive environment. Cracks once initiated can be viewed, Fig. 5, as per the following categories depending upon their location on the surface grain:- i) Transgranular, ii) Inter-granular, iii) and iv) Surface inclusion or pore, v) Grain boundary voids and vi) Triple point grain boundary intersections. The last two are found at elevated temperatures. Models to estimate the number of cycles, Ni , for crack initiation are difficult to develop and initiation life is measured experimentally.

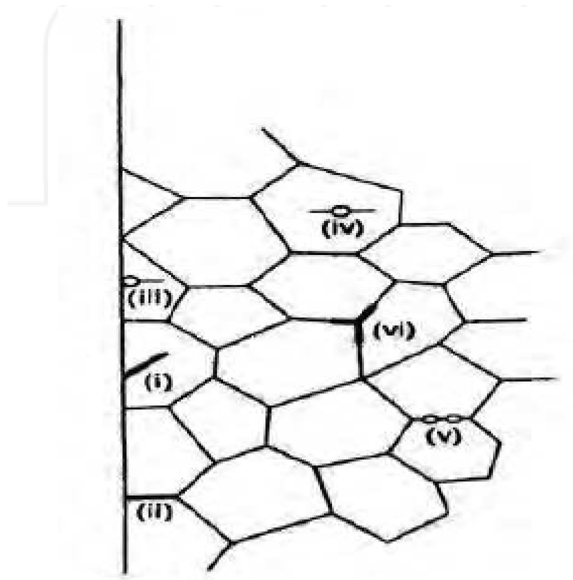


Fig. 5: Crack initiation sites

The process of fatigue failure is characterized by three distinct steps: (1) crack initiation (2) crack propagation, during which this crack advances incrementally with each stress cycle and (3) final failure, which occurs very rapidly once the advancing crack has reached a critical size. The fatigue life Nf , the total number of cycles to failure, therefore can be taken as the sum of the number of cycles for crack initiation Ni and crack propagation Np:

$$N_f = N_i + N_p$$

The contribution of the final failure step to the total fatigue life is insignificant since it occurs so rapidly. Relative proportions to the total life of Ni and Np depend on the particular material and test conditions. At low stress levels (i.e. for high cycle fatigue) a large fraction of the fatigue life is utilized in crack initiation. With increasing stress level, Ni decreases and the cracks form more rapidly. Thus for low cycle fatigue (high stress levels) the propagation step predominates (Np>Ni).

Cracks associated with fatigue failure almost always initiate (or nucleate) on the surface of a component at some point of stress concentration. Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like. In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps which may also act as stress raisers, and therefore as crack initiation sites.

Once a stable crack has nucleated, it then initially propagates very slowly and in polycrystalline metals, along crystallographic planes of high shear stress; this is sometimes termed stage I propagation (Fig. 6). This stage may constitute a large or small fraction of the total fatigue life depending on stress level and the nature of the test specimen; high stresses and the presence of notches favor a short lived stage I. In polycrystalline metals, cracks normally extend through only several grains during this propagation stage. The fatigue surface that is formed during stage I propagation has a flat and featureless appearance.

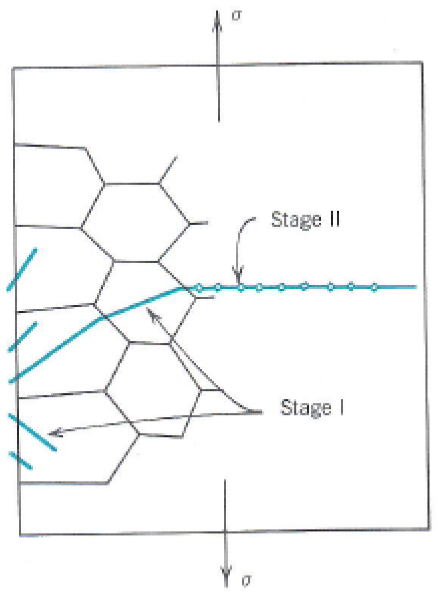


Fig. 6: Schematic representation showing stages I and II of fatigue crack propagation in polycrystalline metals.

Eventually, a second propagation stage (stage II) takes over, wherein the crack extension rate increases dramatically. Furthermore at this point there is also a change in propagation direction to one that is roughly perpendicular to the applied tensile stress (Fig. 6). During this stage of propagation, crack growth proceeds by a repetitive plastic blunting and sharpening process at the crack tip, a mechanism illustrated in Fig. 7. At the beginning of the stress cycle, the crack tip has the shape of a sharp double notch (Fig. 7a). As the tensile stress is applied (Fig.7b), localized deformation occurs at each of these tip notches along slip planes that are oriented at 450 angles relative to the plane of the crack. With increased crack widening, the tip advances by continued shear deformation and the assumption of a blunted configuration (Fig. 7c). During compression, the directions of shear deformation at the crack tip are reversed (Fig. 7d) until, at the culmination of the cycle, a new sharp double notch tip has formed (Fig. 7e). Thus the crack tip has advanced a one notch distance during the course of a complete cycle. This process is repeated with each subsequent cycle until eventually some critical crack dimension is achieved which precipitates the final failure step and catastrophic failure ensues.

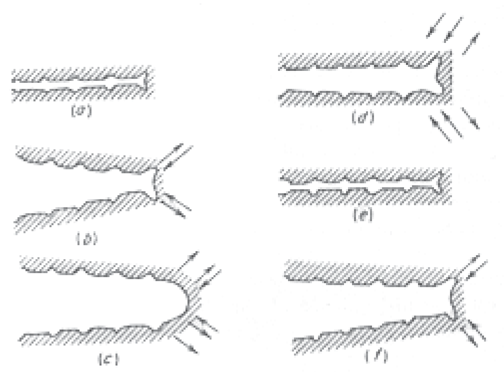
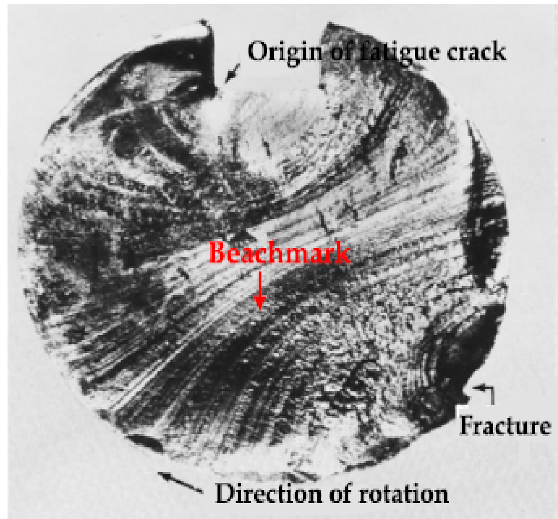


Fig. 7: Fatigue crack propagation mechanism (stage II) by repetitive crack tip plastic blunting and sharpenin

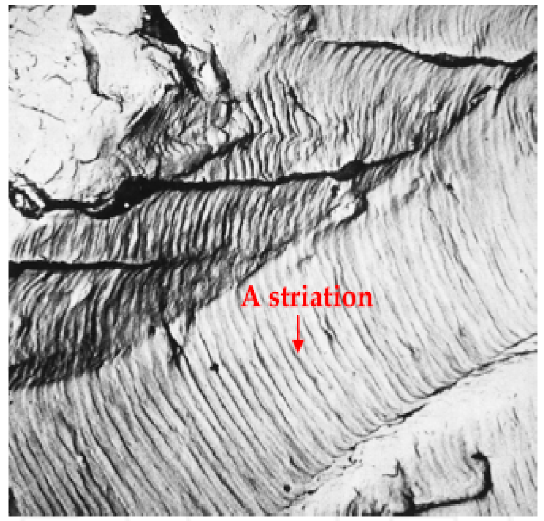
(a) zero or maximum compressive load (b) small tensile load (c) maximum tensile load (d) s

Fractograph of fatigue surface

The surface having fractured by fatigue is characterised by t wo types of markings termed as beachmarks and striations. Both these features indicate the position of the crack tip at some point of time and appear as concentric ridges that expand away from the crack initiation site frequently in a circular or semicircular pattern. Beachmarks are of macroscopic dimensions, Fig. 8a, and may be observed with unaided eye. These markings are found in components that experience interrupted crack propagation e.g. a mac hine that operates only during normal work-shift hours. Each beachmark band represents a period of time over which the crack growth occurs. On the other hand, fatigue striations are microscopic in size, Fig. 8b, and can be viewed with an Electron Microscope. A striation forms a part of beachmark and represents the distance by which the crack advances during the single load cycle. Striation width increases with increasing stress range and vice-versa. Although both beachmarks and striations have similar appearances, they are nevertheless different, both in origin and size. There may be literally thousands of striations within a single beachmark. Presence of beachmarks and striations on a fractured surface confirms fatigue as the cause of failure. At the same time, absence of either or both does not exclude fatigue as the cause of failure.



(a)



(b)

Fig. 8. Fatigue fracture surface of a steel shaft

One final comment regarding fatigue failure surfaces: Beachmarks and striations will not appear on that region over which the rapid failure occurs. Rather, the rapid failure may be either ductile or brittle; evidence of plastic deformation will be present for ductile, and absent for brittle, failure. This region of failure may be noted in Fig. 9.

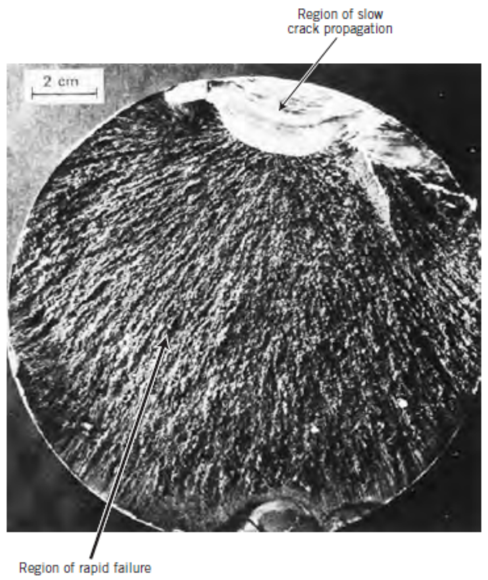


Fig.9: Fatigue failure surface.

A crack formed at the top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture.

Metallurgical Variables of Fatigue Behavior

The metallurgical variables having the most pronounced effects on the fatigue behavior of carbon and low-alloy steels are strength level, ductility, cleanliness of the steel, residual stresses, surface conditions and aggressive environments.

Strength Level. For most steels with hardnesses below 400 HB (not including precipitation hardening steels), the fatigue limit is about half the ultimate tensile strength. Thus, any heat treatment or alloying addition that increases the strength (or hardness) of a steel can be expected to increase its fatigue limit [Fig. 10].

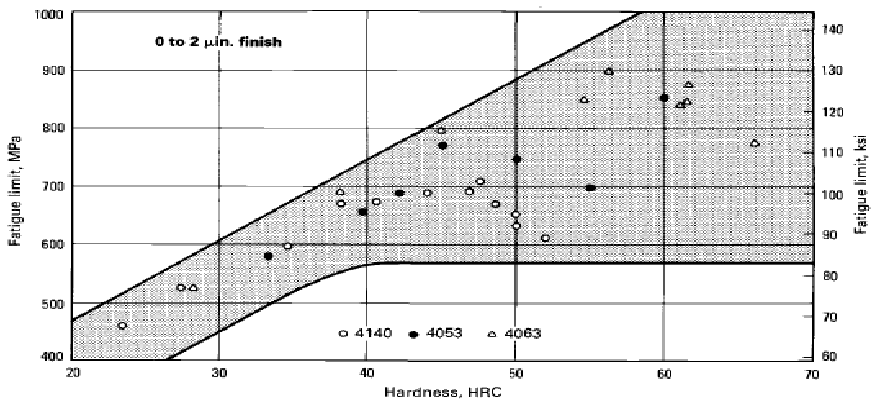


Fig. 16 Effect of carbon content and hardness on fatigue limit of through-hardened and tempered 4140, 4053, and 4063 steels. See the sections "Composition" and "Scatter of Data" in this article for additional discussions.

Fig. 10: Effect of carbon content and hardness on fatigue limit of through hardened and tempered 4140, 4053 and 4063 steels.

Ductility is generally important to fatigue life only under low-cycle fatigue conditions. Exceptions to this include spectrum loading where there is an occasional overload with millions of smaller cycles, or extremely brittle materials where crack propagation dominates.

Cleanliness:

The inclusions in steel generally have a deleterious effect on the fatigue behavior of steels, particularly for long-life applications (Fig.11). The type, number, size, and distribution of nonmetallic inclusions may have a greater effect on the fatigue life of carbon and alloy steel than will differences in composition, microstructure, or stress gradients. Nonmetallic inclusions, however, are rarely the prime cause of the fatigue failure of production parts; if the design fatigue properties were determined using specimens containing inclusions representative of those in the parts, any effects of these inclusions would already be incorporated in the test results.

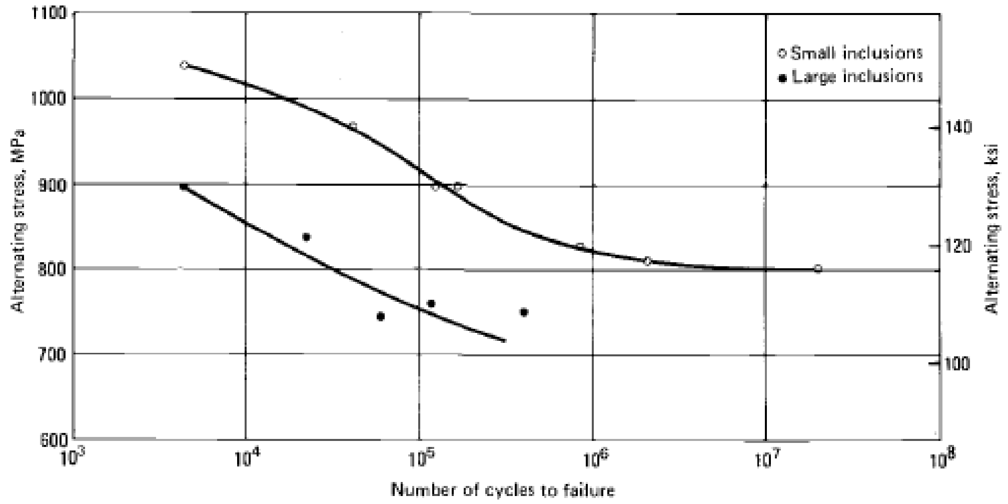


Fig 11: Effect of non-metallic inclusion size on fatigue.

Steels were of two lots of AISI-SAE 4340H; one lot (lower curve) contained abnormally large inclusions; the other lot (upper curve) contained small inclusions.

Surface conditions of a metal part, particularly surface imperfections and roughness, can reduce the fatigue limit of the part. This effect is most apparent for high-strength steels. The inter-relationship between surface roughness, method of producing the surface finish, strength level, and fatigue limit is shown in Fig. 12.

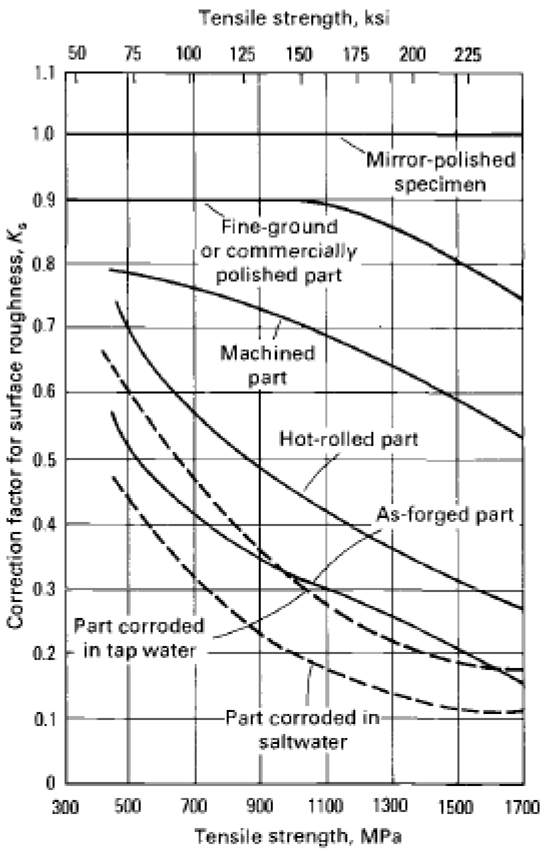


Fig 12: Surface roughness correction factors for standard rotating beam fatigue life testing of steel parts.

Decarburization (depletion of carbon from the surface of a steel part) significantly reduces the fatigue limits of steel (Fig. 13). Decarburization of from 0.08 to 0.75 mm on AISI-SAE 4340 notched specimens that have been heat treated to a strength level of 1860 MPa reduces the fatigue limit. When subjected to the same heat treatment as the core of the part, the decarburized surface layer is weaker and therefore less resistant to fatigue than the core. Hardening a part with a decarburized surface can also introduce residual tensile stresses, which reduce the fatigue limit of the material.

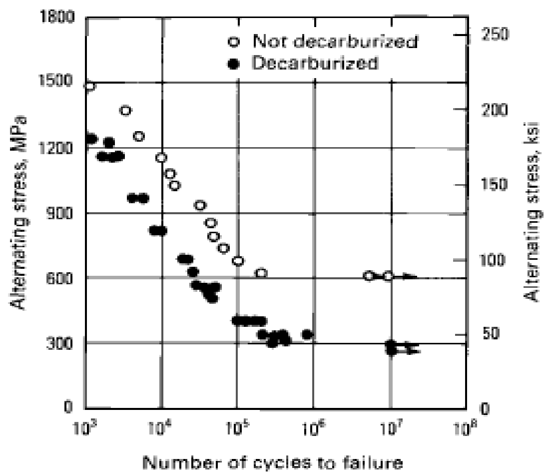


Fig. 18 Effect of decarburization on the fatigue behavior of a steel

Fig.13: Effect of decarburization on the fatigue behavior of a steel.

Fatigue Phenomenon in Materials

Residual Stresses The fatigue properties of a metal are significantly affected by the residual stresses in the metal. Compressive residual stresses at the surface of a part can improve its fatigue life; tensile residual stresses at the surface reduce fatigue life. Beneficial compressive residual stresses may be produced by surface alloying (carburizing, nitriding etc), surface hardening (induction hardening, laser hardening, etc), cold mechanical working (shot peening) of the surface, or by a combination of these processes. In addition to introducing compressive residual stresses, each of these processes strengthens the surface layer of the material. Because most real components also receive significant bending and/or torsional loads, where the stress is highest at the surface, compressive surface stresses can provide significant benefit to fatigue.

Tensile residual stresses at the surfac e of a steel part can severely reduce its fatigue limit. Such residual stresses can be produced by through hardening, cold drawing, welding, or abusive grinding. For applications involving cyclic loading, parts containing these residual stresses should be given a stress relief anneal if feasible.

Aggressive environments can substantially reduce the fatigue life of steels. In the absence of the medium causing corrosion, a previously corroded surface can substantially reduce the fatigue life of the steel.

Grain size of steel influences fatigue behavior indirectly through its effect on the strength and fracture toughness of the steel. Fine-grained steels have greater fatigue strength than do coarse-grained steels.

Composition An increase in carbon content can increase the fatigue limit of steels, particularly when the steels are hardened to 45 HRC or higher (Fig. 10). Other alloying elements may be required to attain the desired hardenability, but they generally have little effect on fatigue behavior.

Microstructure For specimens having comparable strength levels, resistance to fatigue depends somewhat on microstructure. A tempered martensite structure provides the highest fatigue limit. However, if the structure as-quenched is not fully martensitic, the fatigue limit will be lower (Fig. 14). Pearlitic structures, particularly those with coarse pearlite, have poor resistance to fatigue. S-N curves for pearlitic and spheroidized structures in a eutectoid steel are shown in Fig. 15.

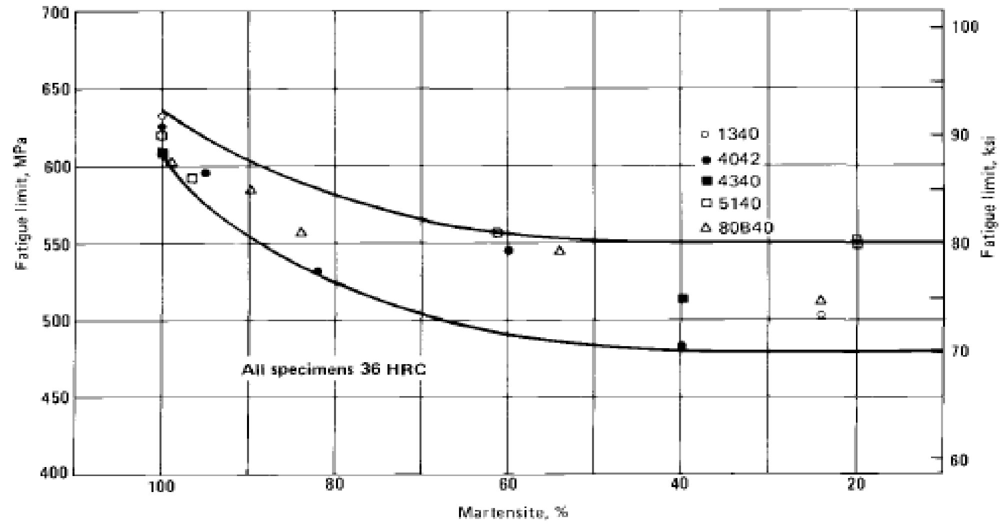
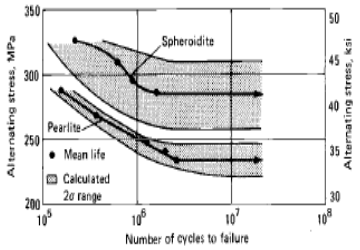


Fig. 14: Effect of martensite content on fatigue limit



Property	Spheroidite	Pearlite
Tensile strength, MPa (ksi)	641 (93)	676 (98)
Yield strength, MPa (ksi)	490 (71)(a)	248 (36)(b)
Elongation in 50 mm (2 in.), %	28.9	17.8
Reduction in area, %	57.7	25.8
Hardness, HB	92	89

(a) Lower yield point. (b) 0.1% offset yield strength

Fig. 23 Effect of microstructure on fatigue behavior of carbon steel (0.78% C, 0.27% Mn, 0.22% Si, 0.016% S, and 0.011% P)

Fig 15: Effect of microstructure on fatigue behavior of carbon steel

Macrostructure:

Ingot cast steels will typically receive much larger reductions in area (with subsequent refinement of grain size and inclusions) than will continuously cast billets when rolled to a constant size. Therefore, the billet size of continuously cast steels becomes important to fatigue, at least as it relates to the size of the material from which the part was fabricated. Research has shown that for typical structural applications, strand cast reduction ratios should be above 3:1 or 5:1, although many designers of critical forgings still insist on reduction ratios greater than 10:1 or 15:1. These larger reduction ratio requirements will frequently preclude the use of continuously cast steels because the required caster size would be larger than existing equipment. While this may not be a major problem at this time, steel trends suggest that there will be very little domestic and almost no off-shore ingot cast material available at any cost within the next two decades. The problem will be reduced as larger and larger casters, approaching bloom and ingot sizes, are installed.

Design against fatigue

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

Design to keep stress below threshold of fatigue limit

Fail-safe, graceful degradation, and fault-tolerant design: To replace parts when they fail. Design in such a way that there is no single point of failure, and so that when any one part completely fails, it does not lead to catastrophic failure of the entire system.

Safe-life design: Design (conservatively) for a fixed life after which the user is instructed to replace the part with a new one ; planned obsolescence and disposable product are variants that design for a fixed life after which the user is instructed to replace the entire device;

Damage tolerant design: 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. The designer sets some aircraft maintenance checks schedule frequent enough that parts are replaced while the crack is still in the "slow growth" phase. This is often referred to as damage tolerant design or "retire ment-for-cause".

Fatigue in Reinforced Concrete Structures

Reinforced concrete structures are widely applied in civil engineering. Highway bridges, railroad bridges, and crane girders are continuously subjected to alternate loads that may cause fatigue fracture of reinforcing steel bars. When the RC structure is under repeated loads, its service life can be significantly reduced for the fracture of reinforcing steel bars.

Ongoing research into fatigue of reinforcement in concrete has been intensified in recent years by the introduction of higher strength materials, the development of advanced applications such as offshore structures and the adoption of new design codes. In addition it is becoming recognised that features such as corrosion, type of bar, form of manufacture, etc. can cause the fatigue lives to be substantially lower than are normally given in reference data.

Although attention has been focussed mainly on the reinforcement bars, consideration must also be given to the fatigue performance of concrete in relation to bridges and highway pavements.

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