Chapter 7 – Fatigue

7.1 General

Repetitive loading of a structure during vibration may bring about its failure at a stress much lower than the static strength. Such a failure can often be attributed to a phenomenon called fatigue. This type of failure has occurred in steel railroad bridges, towers, chimneys and even in highway bridges. Thus it is important to evaluate the stresses due to vibration with regard to fatigue.

Fatigue has much in common with plastic flow and fracture and is essentially a process of slip within the crystals along the direction of the greatest shear. In static fracture, the slip formation is spread throughout a large volume of the metal and is accompanied by readily recognizable distortions such as contraction of the cross-section; in fatigue, the slip formation is confined to a small localized volume, the fracture plane is characteristically smooth and the metal suffers no distortion (Fig. 7.1).

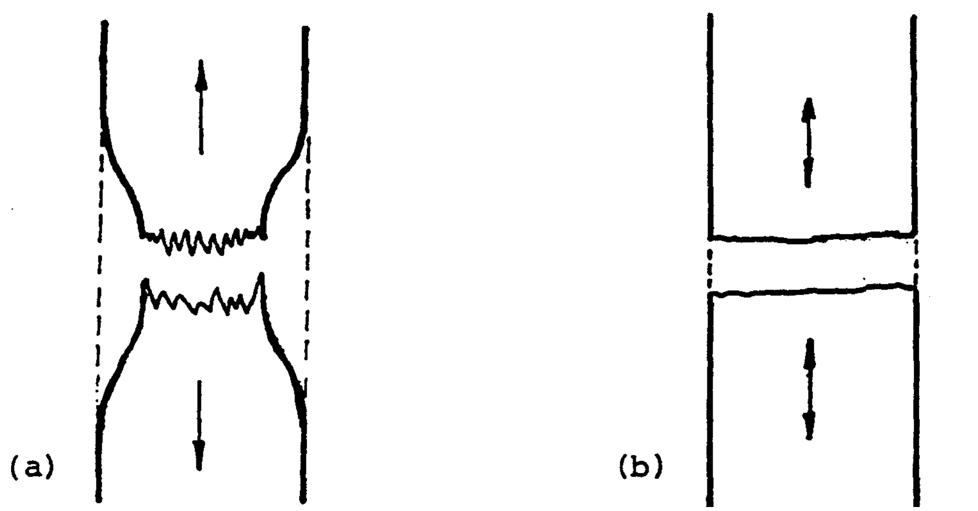

Fig. 7.1 Modes of failure: (a) - static failure in tension test, (b) - fatigue failure due to repetitive loading

The fatigue process, from the first loading cycle to rupture, has three distinct stages. In the *first stage,* slip formation occurs within the interior of the grains if the frequency of load application is higher than about 400 cycles per minute; at lower frequencies, the slip formation extends from one grain boundary to the next as in static tests.

The *intermediate stage* occupies the major part of fatigue life. The slip formation becomes localized. The original small number of slip lines, formed in the first stage, begin to thicken into bands and a *microscopic crack* appears. This crack starts growing in a zig-zag form and the average direction at right angles to the tensile stress.

In the *final stage,* the microscopic crack grows into a *macroscopic* crack which rapidly spreads into the bulk of the metal rendering it unable to carry the load; an abrupt failure follows.

The tendency to fatigue failure can be described in terms of fatigue limit or fatigue strength.

Fatigue or *endurance limit* is the alternating stress which can be applied indefinitely without failure occurring; 10^6 loading cycles is usually considered to be sufficient to define the fatigue limit.

Fatigue strength is the nominal alternating stress which produces failure for a specified number of cycles (Fig. 7.2). Alternatively, fatigue strength may be given in terms of *fatigue ratio* which is the ratio of the fatigue strength to the ultimate strength.

Fatigue limit and fatigue strength depend on a number of factors. The first one is the type of loading (Fig. 7.3). As can be seen, torsional loading reduces the available strength most but even bending reduces the fatigue strength to about one half of static strength. Surface roughness has a profound effect; fatigue limit increases with increasing smoothness of the surface but increases only marginally with static strength (grade of the steel) if the surface is not machined (Fig. 7.4). Thus the choice of higher grade steel need not eliminate the danger of fatigue.

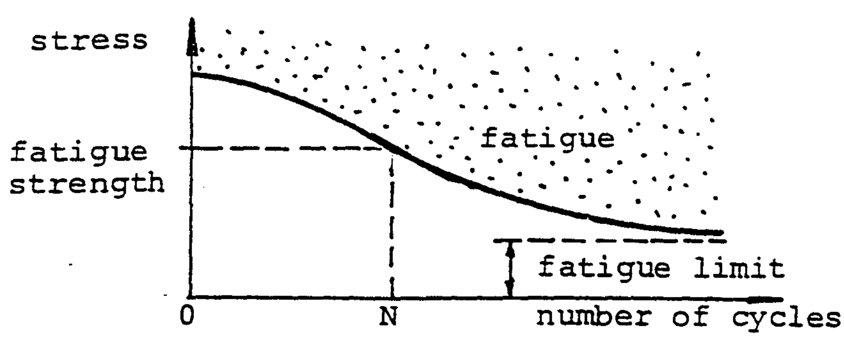

Fig. 7.2 Schematic of fatigue limit and fatigue strength

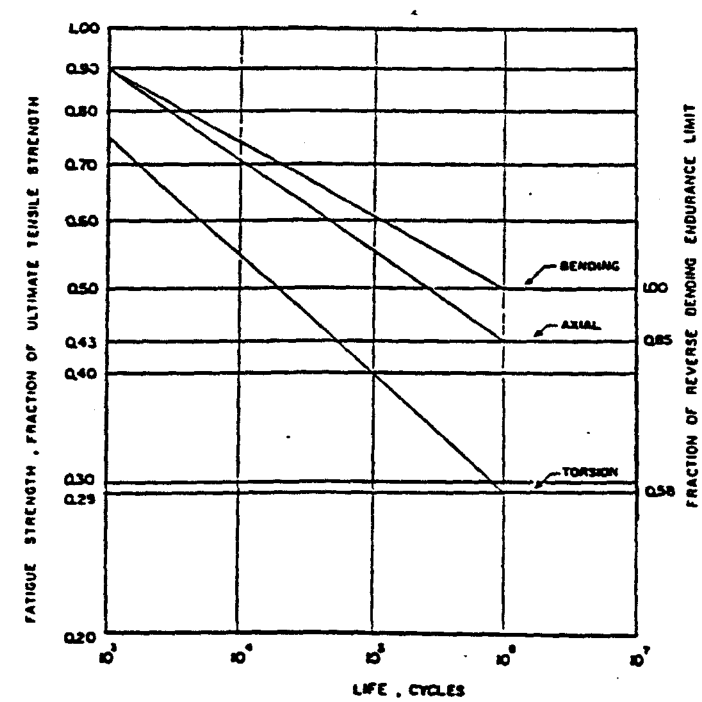

Fig. 7.3 Fatigue strength for basic types of loading

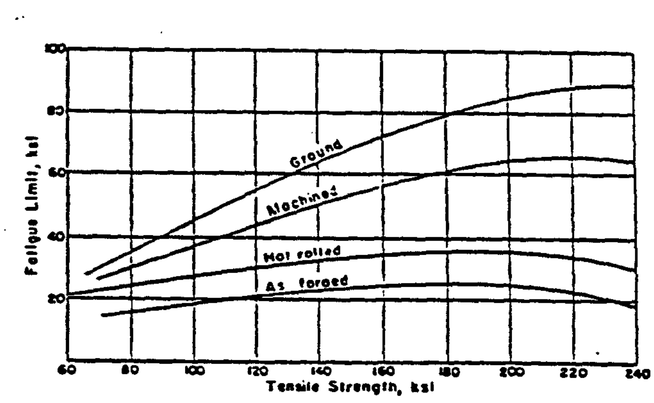

Fig. 7.4 Variation of fatigue limit with surface roughness and tensile strength

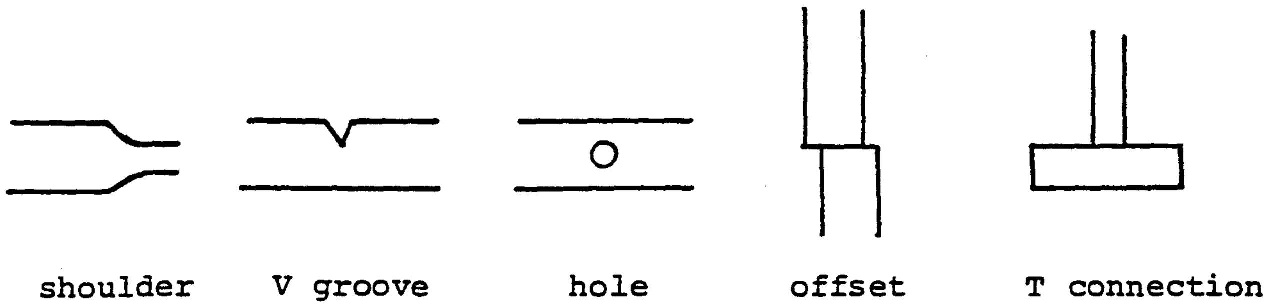

Fig. 7.5 Typical notches reducing fatigue strength

Fatigue strength is further reduced by stress concentration, which may be caused by various notches (Fig. 7.5). The sensitivity of different materials to notches is not the same and is characterized by notch sensitivity index.

Stress range applied in cyclic loading is the most important factor for any specimen; the mean value of the stress seems fax less important than had been thought until recently (Fig. 7.6).

The effect of weldments on the fatigue strength *of* steel structures is a very unfavourable factor. This is so because welding provides the initial flaws and defects which alleviate the need for the first stage of the fatigue process. Sharp defects exist at the weld periphery or in the weldment and occur regularly even in the common fillet and groove (V-butt) welds. At these defects, the crack growth starts. The initial flaws are sharp intrusions of slag or porosity (gas pockets) and may also result from weld repairs with incomplete fusion. These defects occur at the flame-cut edges of plates as well.

For these reasons cover plates, stiffeners and various attachments, such as those shown in Fig. 7.7, can reduce the fatigue strength to 1/2, 1/3 or even more of the fatigue strength of the plain welded beam (Fig. 7.6 from: J.W. Fischer et al. Effect of Weldments on the Fatigue Strength of Steel Beams," Nat. Coop. Highway Research Program Report 102, Highway Research Board, Nat. Academy of Engineering, 1970, p. 114). Considerable improvement can be achieved by sealing the root of the weld and machining the surface (Fig. 7.8).

Experimental observations depend on test conditions and details which lead to large scatter of results and a high degree of uncertainty. This is why statistics is increasingly used to evaluate the results of fatigue tests and to predict fatigue life of a structure. Further information on fatigue can be found in *Refs. 11* and 12.

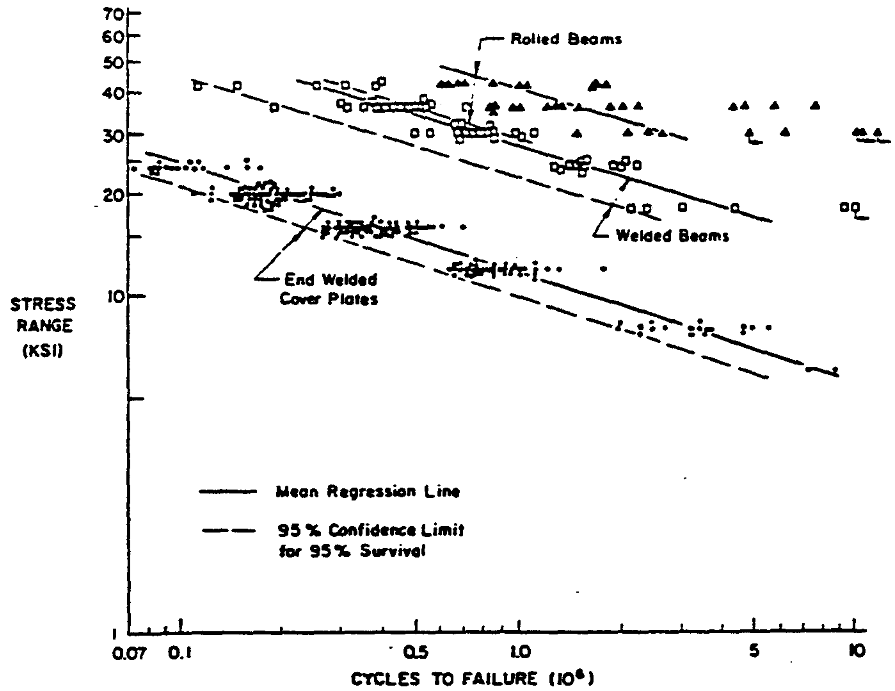

Fig. 7.6 Mean fatigue strength and 95 percent confidence limits in terms of stress range for rolled, welded and cover plated beams (J.W. Fisher et al., 1970)

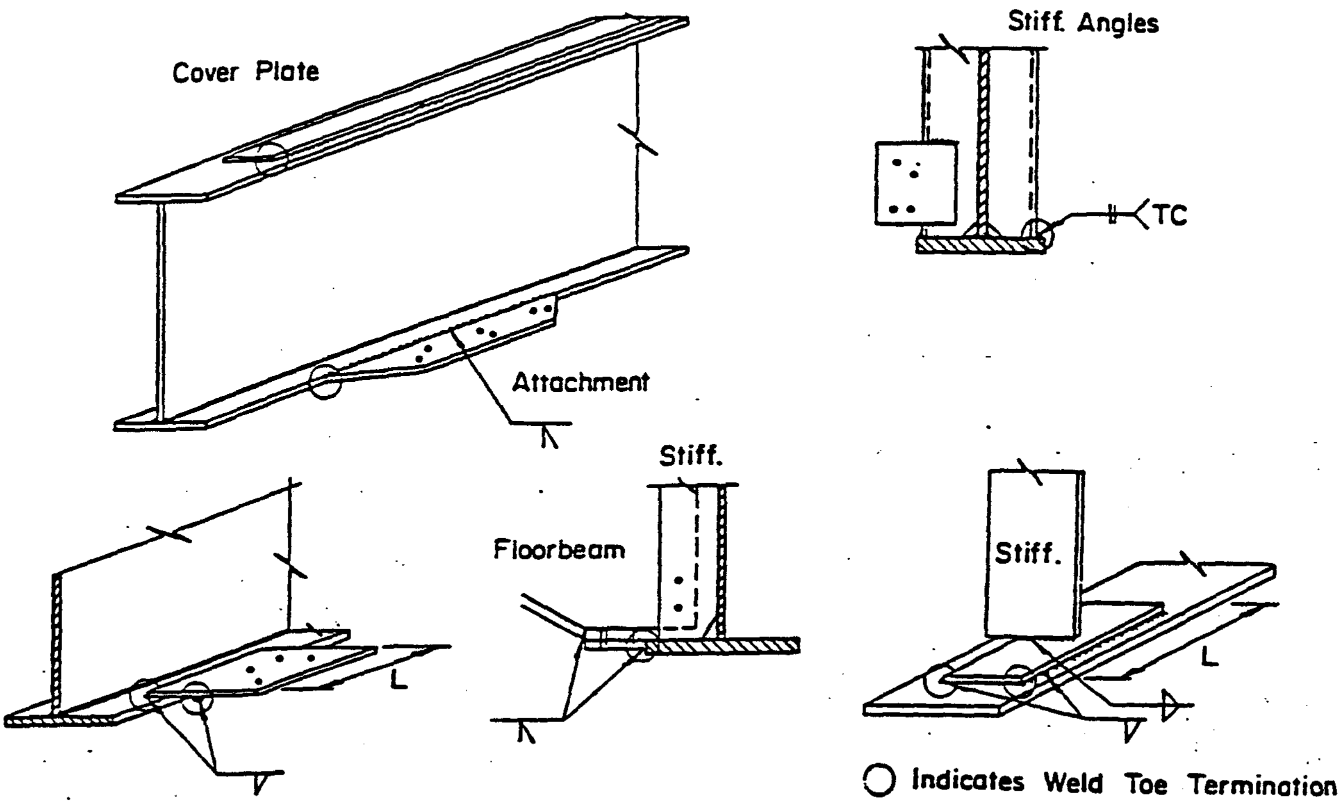

Fig. 7.7 Typical details that reduce fatigue strength of beams (J.W. Fisher et al., 1970)

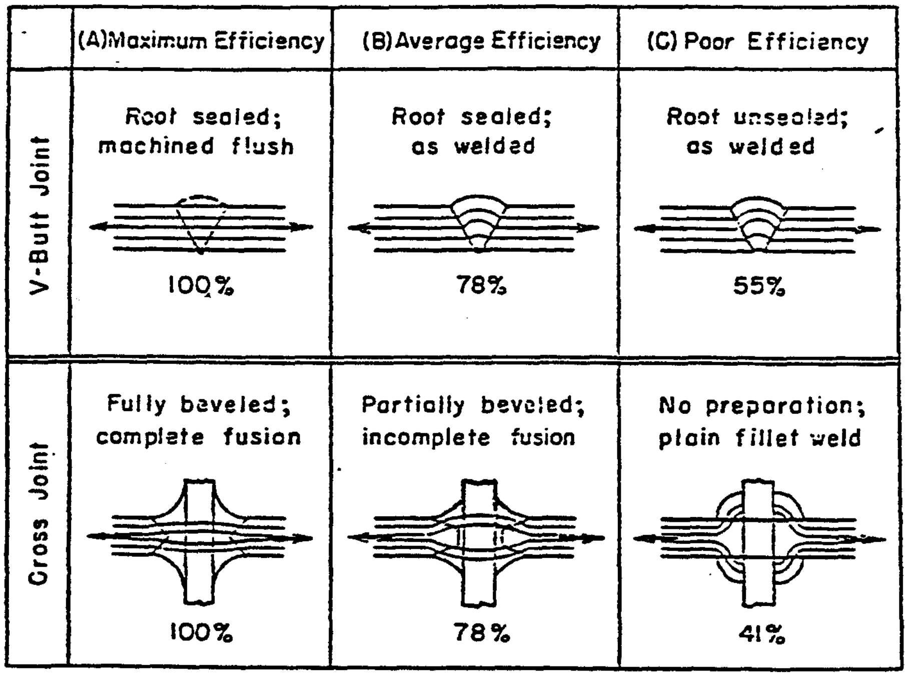

Fig. 7.8 Effect of weld contour and defects on stress flow lines and fatigue behaviour of welded joints

<u>Brittle Fracture</u>. In a normal case of static overloading, the imminent failure is fairly well predictable, because visible yielding, sag or cracks precede the collapse. The brittle fracture, somewhat like a fatigue failure, occurs suddenly and without visible signs of any imminent failure. Brittle failure, meaning a fracture without yielding, can occur when <u>low temperatures</u> and <u>peak stresses</u> exist. The peak stresses are produced by stress raisers such as weld cracks, fatigue cracks, flaws or notches.

The material capability to resist brittle fracture depends on *toughness.* Toughness represents the capability to take the load even in the presence of flaws, notches or cracks and can be established by special standardized tests.