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Comments on Low Cycle Fatigue and Brittle Fracture of Structures

Commentaire à la fatigue à basse fréquence et sur la rupture fragile de structures

Kommentar zur niederzyklischen Ermüdung und zu Sprödbrüchen an Tragwerken

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During the Symposium there has been frequent reference to low-cycle fatigue experienced by bridges and buildings but comparatively little attention has been given to what is actually meant by low-cycle fatigue. The classical definition is failure occurring in less than 10,000 cycles of repeated load so that the fatigue regimes can be expressed as:-

Low cycle fatigue < 10,000 cycles < High cycle fatigue

In his introduction to Session 5, Ferry Borges referred to the principal law of low cycle fatigue as being that of Manson-Coffin.⁽¹⁾ However, the situation is rather more complex because this can only be applied when the cycles are between fixed limits of strain. The most common form of fatigue in structures is almost certainly pulsating tensile loads (fig 1).

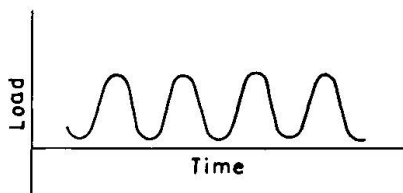


Fig. 1 PULSATING TENSILE LOAD

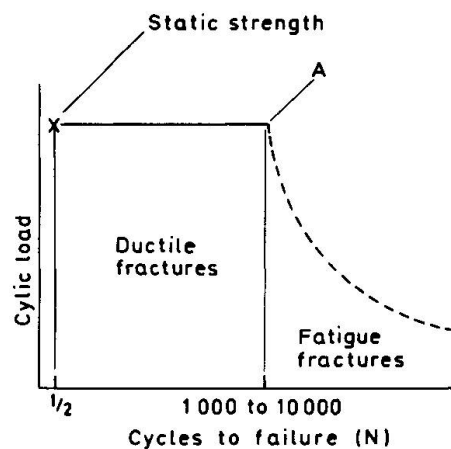


Fig. 2 FATIGUE RUPTURE CURVE FOR PULSATING TENSILE LOAD

This gives rise to a characteristic shape of fatigue curve which is common to all engineering materials (fig 2) which can be described by the equation:

$$N = \frac{n f t_c (1 + \beta/\kappa)}{n + f t_c (1 + \beta/\kappa)}$$

Where N is the number of cycles to failure

f is frequency

t_c is the life under static load

n is the extrapolated high cycle fatigue life

β and κ are stress and time exponents

The derivation of this equation is given in reference 2. The cyclic action produces work-hardening of structural steel as exhibited by the hysteresis loops and cumulative strain curve shown in fig. 3.

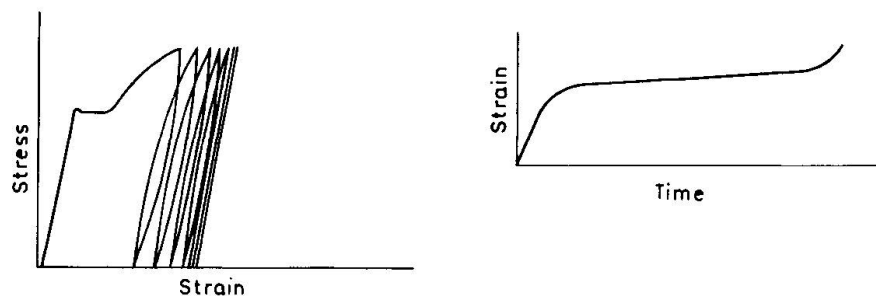


Fig. 3. HYSTERESIS LOOPS FOR PULSATING TENSILE LOAD AND DEVELOPMENT OF CUMULATIVE STRAIN

The sharp discontinuity in the fatigue curve (A in fig 2) occurs at $\sim 10,000$ cycles for a wide range of advanced alloys and at $\sim 1,000$ cycles for structural steel. This is associated with a change from ductile internally initiated fracture at the high stresses to low ductility fatigue fractures. It can be seen that behaviour at the low endurances is very sensitive to stress and levels a few per cent below the static strength can give lives beyond the discontinuity. Under these circumstances, it is clear that some of the work described in this symposium, involving 10 to 20 repetitions of load, did not produce significant damage and it is not surprising that subsequent tests to destruction exhibited little or no change in strength.

Cycles between fixed limits of deformation occur in situations where there is an imposed restraint such as in thermal fatigue or some types of composite material. At endurances below 10,000 cycles, plastic deformation is involved and repetitions of tensile strains cause the material to shake down to a push-pull load condition which is enhanced by the Bauschinger effect as shown in fig 4. This involves the development of compressive stress in the presence of tensile strain.

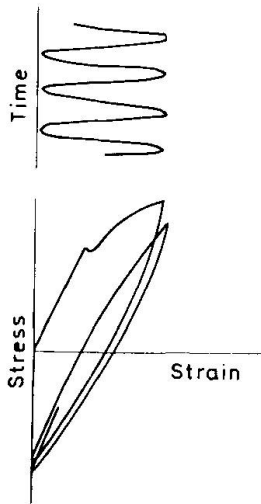


Fig.4 HYSTERESIS LOOPS FOR PULSATING TENSILE STRAIN

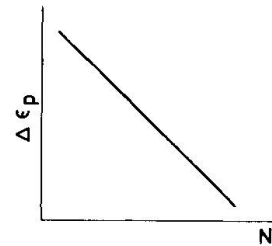


Fig.5 FATIGUE RUPTURE CURVE FOR PULSATING TENSILE STRAIN

Manson and Coffin showed that the resulting rupture data (fig 5) can be represented by the equation:

$$\Delta \epsilon_p N^\alpha = \text{Const.}$$

where $\Delta \epsilon_p$ is the plastic strain range and α was originally proposed as 0.5 but was later modified to 0.6.

It is clear from the above that it is most important to identify whether the low-cycle fatigue is due to load cycling or strain cycling. In practice, it is doubtful whether true low-cycle fatigue occurs in bridge structures and such high stresses as do occur are most likely to be produced by repetitions of load.

Finally, references have been made to the likelihood of brittle fracture occurring in steel components. Brittle fracture occurs when materials having crystallographic systems other than face centred cubic, fail on (100) planes. Such failures involve very little absorption of energy and little or no ductility. Normally, structural steels fail on (110) shear planes. One of the first recorded brittle failures of a bridge structure was of the Hasselt Bridge, Belgium, in 1938. Here failure occurred when the air temperature was -20°C . Although there has been extensive research into brittle fracture in the past two decades, there is comparatively little awareness of its interaction with fatigue. McGregor⁽³⁾ showed that material subjected to different degrees of high cycle fatigue exhibited increases in brittle-ductile transition temperature of up to 46°C . In a later investigation, it was found that increases of up to 30°C can occur for structural steels subjected to low-cycle fatigue.⁽⁴⁾ However, the situation was shown to be rather more complex because some types of fatigue were beneficial.

In conclusion, the purpose of this contribution to the discussion is to draw attention to:-

- (1) The importance of determining what type of cycle is relevant if low-cycle fatigue is involved.
- (2) The increased risk of brittle fracture that can arise if there is a prior history of fatigue.

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