

CUMULATIVE FATIGUE DAMAGE IN SEISMIC STRUCTURES

by

Mubadda Suidan^I and Robert A. Eubanks^{II}

SYNOPSIS

The viability of cumulative fatigue damage as a design criterion for single degree of freedom steel structures is investigated. Critical section strain and stress histories due to artificial earthquake excitation are obtained and their damage is evaluated by a model incorporating the rain flow cycle counting method. Correlations of damage and a hysteretic dissipated energy parameter on the one hand and damage and ductility on the other are presented. The range of natural period of vibration of the structures in which fatigue damage is appreciable is defined.

INTRODUCTION

Seismic structures are currently designed to withstand the maximum forces induced in them by seismic excitation. The time history of the structures' response to seismic excitation receives very little attention. The time history response may indicate that, although the structure is capable of withstanding the maximum forces involved, it may fail due to cumulative fatigue damage or by incremental collapse.

This investigation is concerned with the cumulative fatigue damage aspect of single degree of freedom seismic structures manufactured of steel. Earlier investigations of the problem (2,4) do not incorporate recent developments in fatigue analysis. In this investigation single degree of freedom "shear beam" structures (SDF) are excited by two ensembles of generated earthquake acceleration records. The structures are made of SAE 1015 steel for which a median strain-fatigue life function is employed.

GENERATED EARTHQUAKE RECORDS

The number of strain reversals experienced at a critical section of a SDF seismic structure is small. Hence the

^I Project Engineer, Consolidated Engineering Co., Beirut, and
Lecturer, American University of Beirut, Beirut, Lebanon

^{II} Professor of Civil Engineering and Theoretical & Applied
Mechanics, University of Illinois, Urbana, Illinois, USA.

section will experience appreciable fatigue damage due to a seismic excitation only if the strain reversal amplitudes are large. The generated earthquake records were therefore designed to represent large magnitude earthquakes of long duration. Ten records for each of two ensembles were generated: Type I records having 120 second durations and maximum accelerations ranging from 0.40g to 0.55g where g is the gravitational acceleration; and Type II records having 50 second durations and maximum accelerations ranging from 0.28g to 0.35g. The procedure for the generation of the records closely followed that proposed by Jennings, et al (3). The individual record characteristics are presented elsewhere (9).

DAMAGE MODEL

The cumulative fatigue damage model used incorporates the following features: Total strain amplitude-fatigue life curves; strain reversal counting in accordance with the rain flow cycle counting method; the mean stress effect; and the effect of the ordering of the strain reversals in the strain history.

Fatigue life curves are constructed in terms of the total number of strain reversals to failure, $2N_f$, and the elastic and plastic strain amplitudes, $\Delta\epsilon_e/2$ and $\Delta\epsilon_p/2$ respectively. This construction is due to Morrow (7) and is represented by the following relationship for $\Delta\epsilon/2$, the total strain amplitude.

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\epsilon_e}{2} + \frac{\Delta\epsilon_p}{2} = \frac{\sigma_f'}{E} (2N_f)^b + \epsilon_f' (2N_f)^c \quad (1)$$

where σ_f' is the fatigue strength coefficient, ϵ_f' is the fatigue ductility coefficient, E is Young's modulus, and b and c are experimentally obtained exponents. The fatigue life relationship for SAE 1015 steel, presented by Keshavan (5), and modified to suit the Morrow criteria, is as follows (see Fig.4):

$$\frac{\Delta\epsilon}{2} = 0.76(2N_f)^{-0.58} + 0.0035(2N_f)^{-0.085} \quad (2)$$

The rain flow cycle counting method (1,6,9) was one of a number of counting methods investigated by Dowling (1). He determines that two methods, the rain flow and the range pair methods, predict fatigue lives close to actual test fatigue lives. The rain flow method, however, is the better of the two for strain histories comprised of only a few irregular reversals or for those which have insignificant minor reversals such that the damage is largely due to a few major reversals. The strain histories of extreme fibers at critical sections of seismic structures are clearly of the type to which the rain flow cycle counting method is the most applicable.

A factor to allow for the effect of the mean stress of a strain reversal similar to that suggested by Morrow (9) is incorporated in the model. Use of the rain flow counting method, however, results in only the insignificantly small amplitude strain reversals having a non-zero mean stress. The influence of this factor is therefore negligible.

Another factor is introduced in the damage model to allow for the reduction in the expected fatigue life of a steel prestrained by a few plastic strain reversals. It involves the rotation of the fatigue life-strain curve to make it steeper. The influence of this rotation was found to be not significant, however.

SDF FRAME CHARACTERISTICS

Shear type SDF frames are considered in this investigation (see Fig.1). Their characteristics are an infinitely large beam moment of inertia; a concentrated mass at beam level; identical columns of W section having a flange width equal to half the web depth and flange and web thicknesses in accordance with those used by Kasiraj and Yao (4); both columns are rigidly connected at their extremities; displacements due to shear are ignored; axial column loads are considered to be negligible; and the column flanges are assumed to be sufficiently braced against flange buckling. The governing equation of motion of the SDF frame is

$$\ddot{x} + 2\eta \sqrt{\frac{k_j}{m}} \dot{x} + \frac{1}{m} Q(x) = -\ddot{y} \quad (3)$$

where x is the coordinate of horizontal motion of the concentrated mass relative to the columns, y is the coordinate of horizontal ground motion, $Q(x)$ is the frame restoring force function (see Fig.2); $k_j = d/dx Q(x_j)$ and η is the proportion of critical damping in the frame.

The SDF frame strength factor, ϕ , is defined as the ratio of $Q(x_y)$, the value of $Q(x)$ at the point when the critical column section begins to yield, and the product of the mass, m , of the frame and g . The strength factor may be related to minimum code requirements (9) and to the initial natural frequency of the frame, ω_0 , which is obtained as $\sqrt{Q(x_y)/x_y \cdot m}$. The natural initial period of vibration, T_0 , is defined as $2\pi/\omega_0$.

Rules for the design of seismic structures have been proposed (11). Their application calls for the partition of the design earthquake spectrum into low, medium and high period ranges. Structures falling in the low period range are very sensitive to variations in the yield level, $Q(x_y)$, and are designed to have a maximum displacement response well below x_y and hence are not susceptible to any significant fatigue damage. Structures whose T_0 fall in the

medium period range are more likely to incur high fatigue damage levels. The lower limit of this range for the Type I and Type II earthquake ensembles is at about $T_0 = 0.4$ seconds. Kasiraj and Yao (4) indicate that insignificant amounts of fatigue damage are incurred in structures having a value of $T_0 = 2.0$ seconds. These values of T_0 are related to ϕ and to practical frame height to column depth ratios to obtain the following ranges which are used in this investigation:

$$\begin{aligned} 0.4 \text{ seconds} < T_0 < 2.0 \text{ seconds} \\ 0.05 < \phi < 0.15 \end{aligned}$$

Finally, the stress-strain relationship of the material is idealized to be elastic - perfectly plastic as is shown in Fig.3 where the corresponding static and fully cycled stress-strain relationships are also shown.

PRESENTATION AND DISCUSSION OF RESULTS

The displacement history of the center of mass of the SDF frame is obtained by the numerical integration of Eq.3 by Newmark's Beta method (8). At points of displacement reversal the critical section strains and stresses are obtained and are evaluated by the damage model. Damage greater than unity is considered to indicate fatigue failure and maximum strain amplitudes in excess of 0.30 are considered to indicate a maximum single excursion failure. Also evaluated from the stress-strain history is the hysteretic energy dissipated in one cubic inch of flange steel, HECC. The ductility required of the structure to avoid a maximum excursion failure is obtained from the displacement history. Cumulative fatigue damage estimates resulting from excitation by the earthquake record ensembles are presented in Fig.5. In Fig.6 this damage is correlated with the corresponding values of HECC, and is also correlated with the required ductility in Fig.7.

The good correlation between damage and HECC, and damage and ductility, is a direct consequence of the application of the rain flow cycle counting method (10). Damage is largely a result of the few large amplitude strain reversals. The energy parameter, HECC, may be expressed as the product of a material-- and section-related constant and the summation of plastic strain reversals (9) and hence reflects the large amplitude strain reversals which contain most of the plastic strain of the strain history. Similarly, ductility is related to the maximum strain reversal point which is at the largest amplitude displacement.

In the investigation reported on herein the columns are assumed to have negligible axial loads. Yamada (12), however, notes that columns having large axial loads have shorter fatigue lives than columns having smaller axial

loads for the same displacement amplitude. It is possible to explain this phenomenon in part by an application of the rain flow cycle counting method to the strain history which now includes the cumulative axial strain (10). This is illustrated in Fig.8.

CONCLUDING REMARKS

It has been shown that fatigue in SDF seismic structures designed according to the rules suggested by Veletsos and Vann (11) and having initial natural periods of vibration at the lower end of the medium period range of the design earthquake spectrum is significant. The damage is evaluated using virgin steel properties. Joint features such as welding, bolts, etc., are detrimental to the fatigue life of metals and hence the damage obtained at actual joints is probably much higher than that indicated in Fig.5.

Fatigue damage may be estimated from relationships pertaining to the required ductility of a structure or to the hysteretic dissipated energy at critical frame sections. The estimates introduce small inaccuracies but are much easier to obtain.

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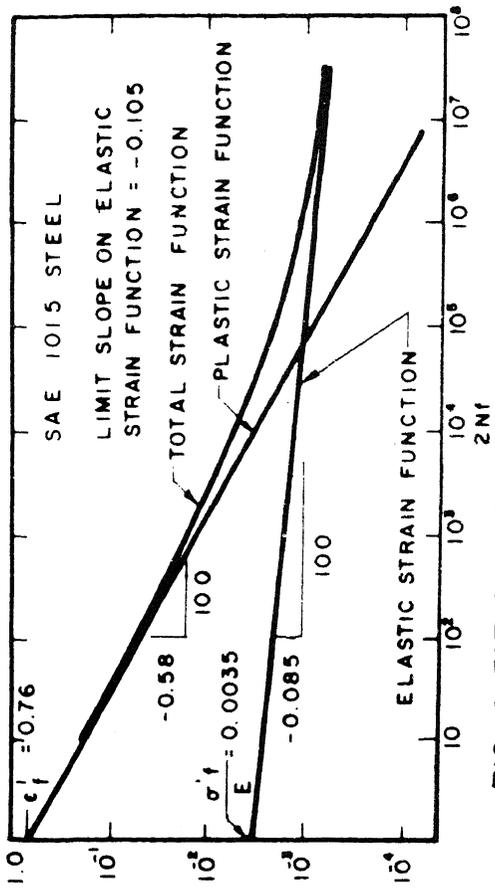


FIG. 4 FATIGUE PROPERTIES OF SAE 1015 STEEL.

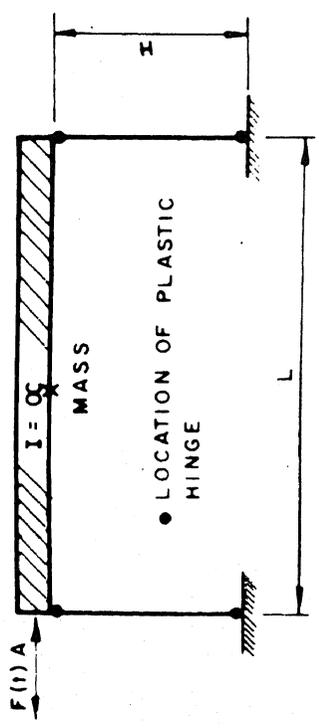


FIG. 1 SDF FRAME STRUCTURE

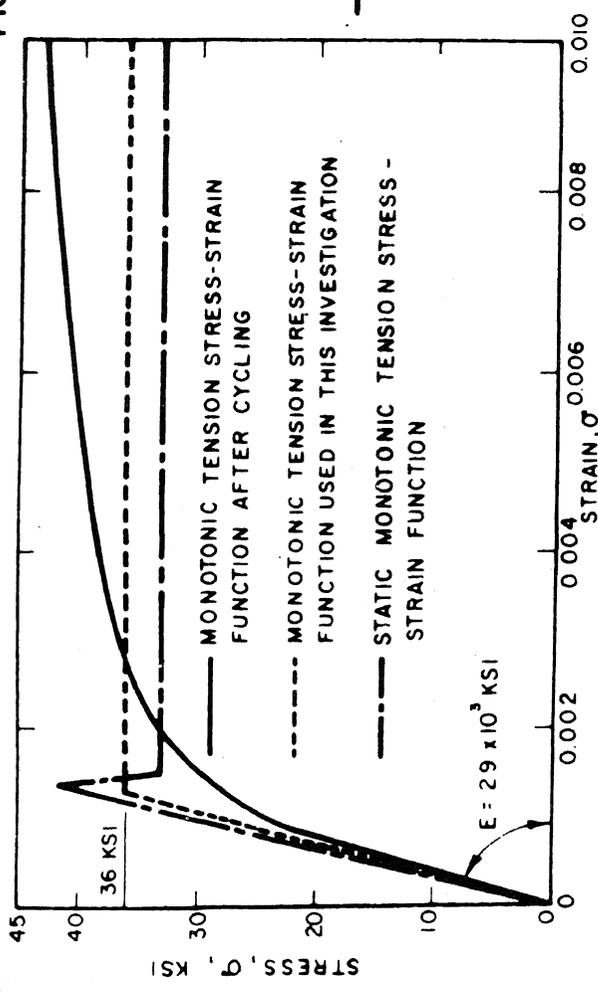


FIG. 3 STRESS STRAIN RELATIONSHIPS FOR SAE 1015 STEEL

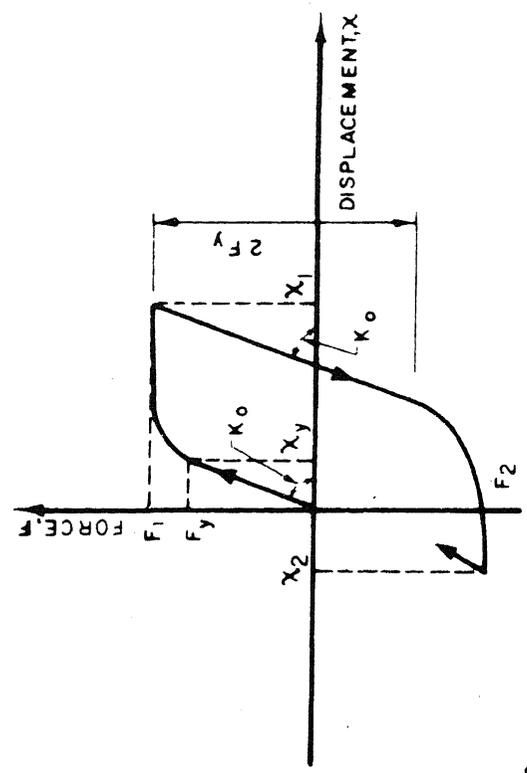
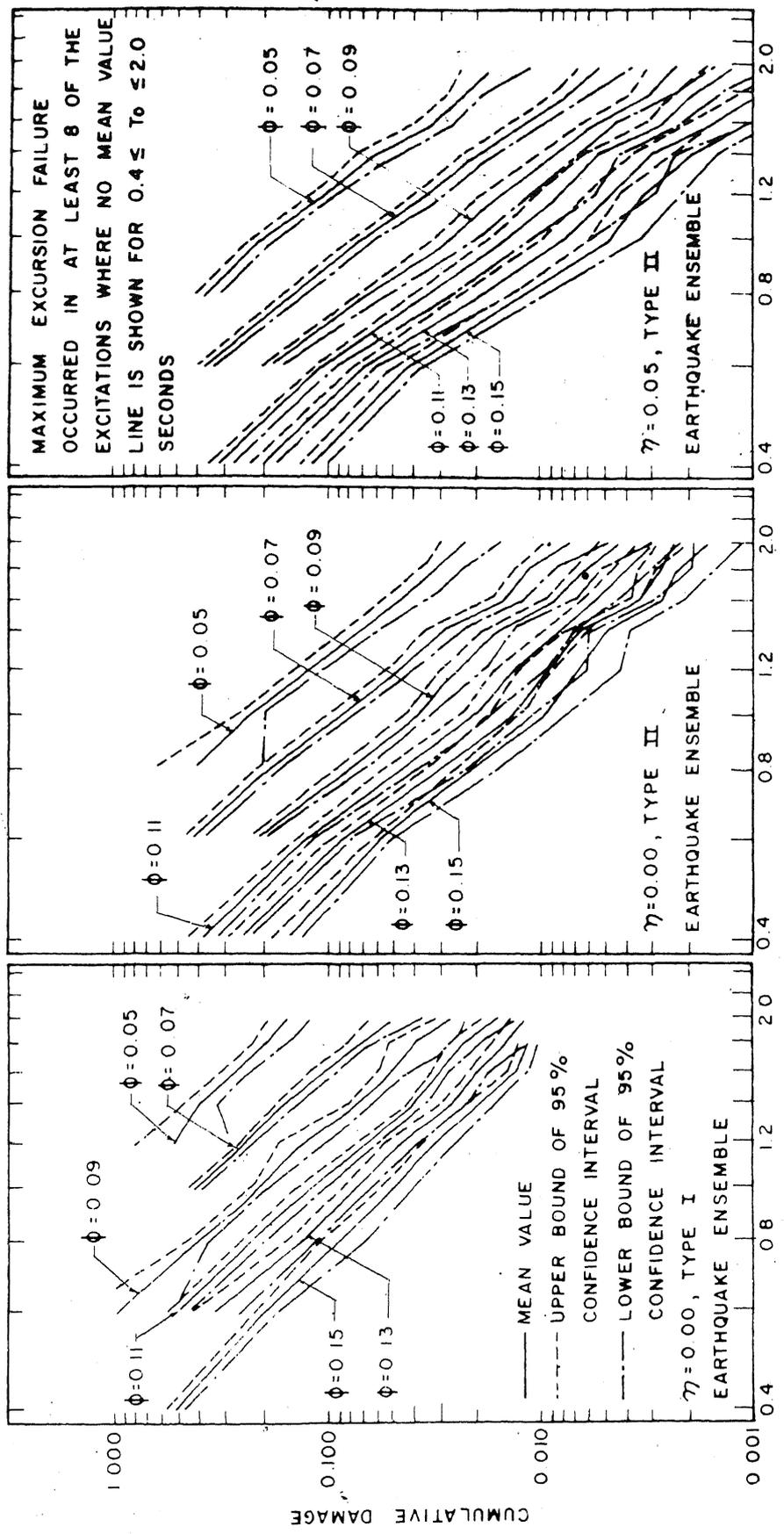


FIG. 2 RESTORING FORCE FUNCTION, Q (X)



T_0 , SEC.

(A) (B) (C)

FIG. 5 CUMULATIVE DAMAGE DUE TO EXCITATION BY SIMULATED EARTHQUAKE ENSEMBLES

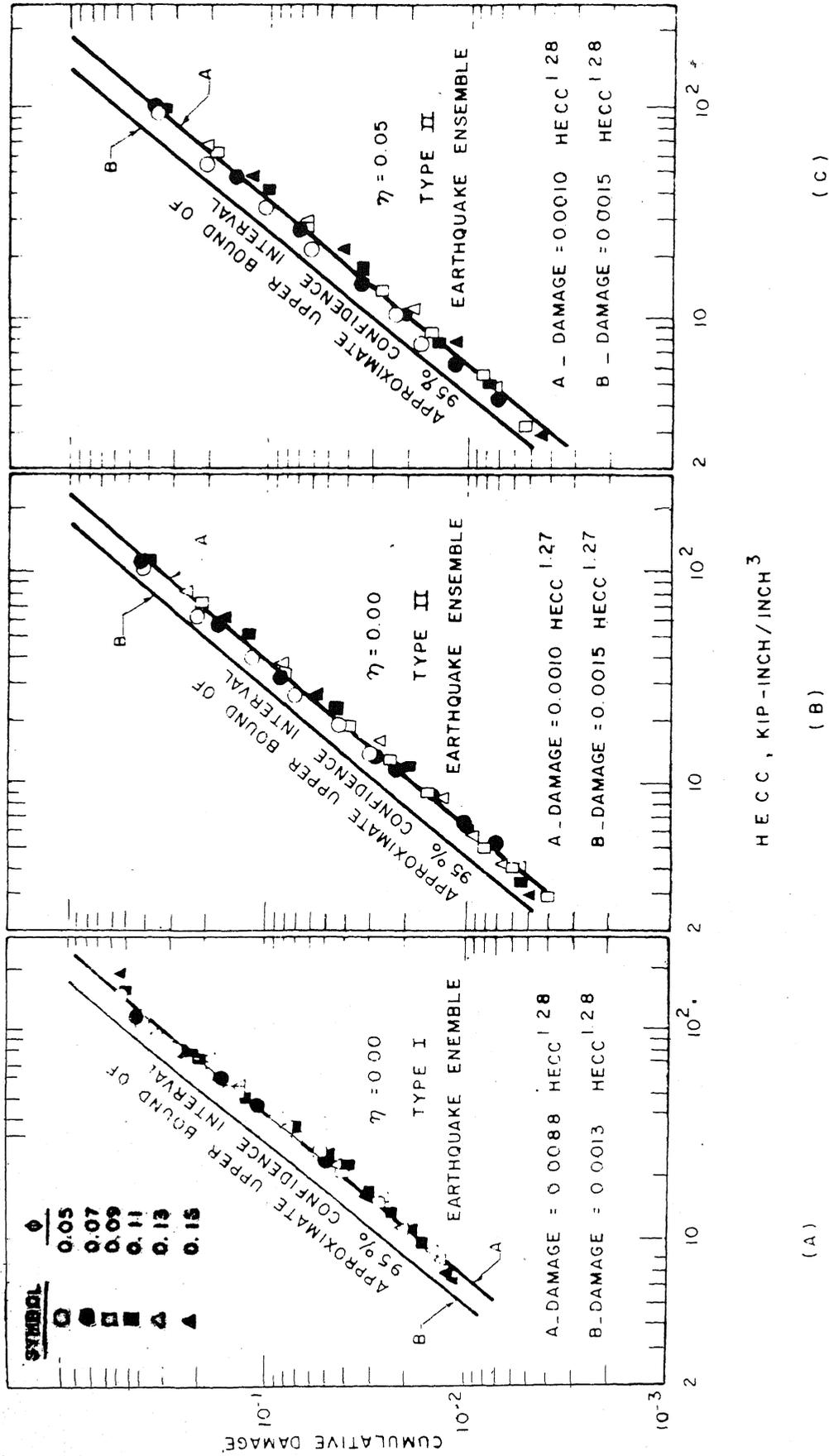


FIG. 6 CUMULATIVE DAMAGE VS. HECC

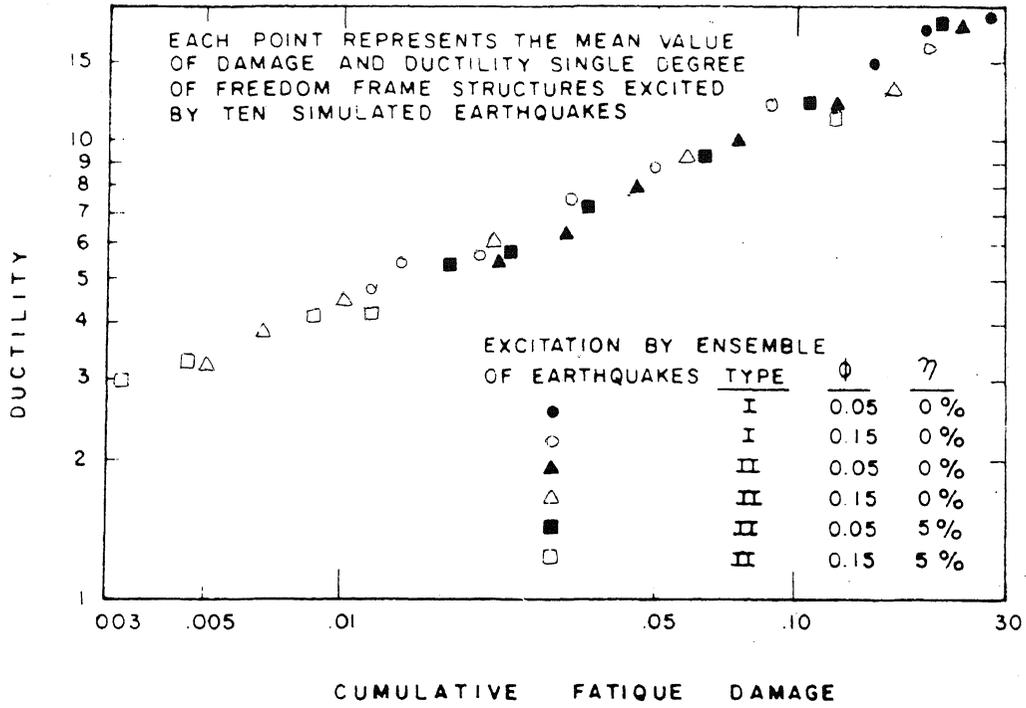


FIG. 7 CORRELATION OF CUMULATIVE FATIGUE DAMAGE & DUCTILITY

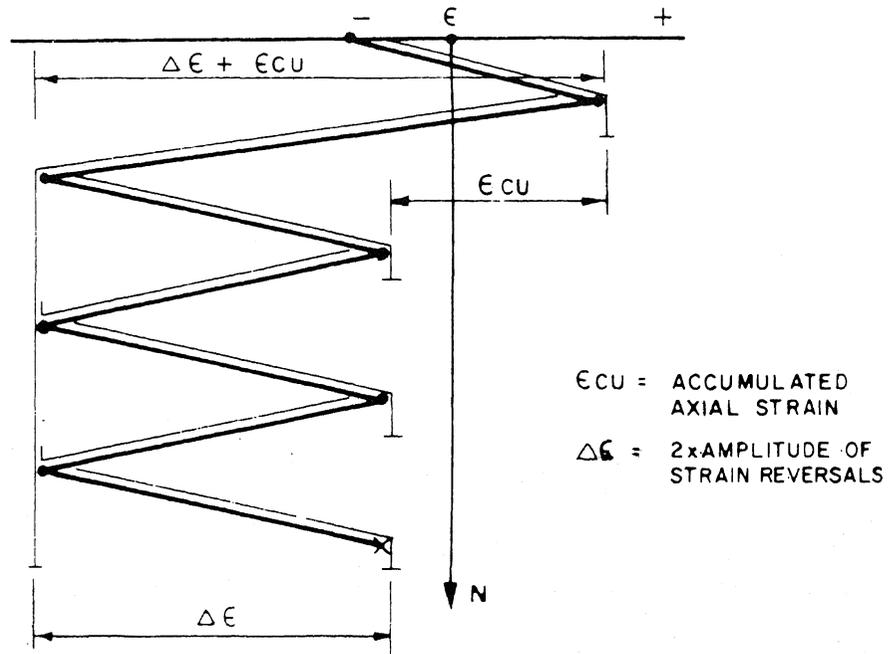


FIG. 8 STRAIN HISTORY WITH ACCUMULATED AXIAL STRAIN