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Paper No.694. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EQUIVALENT DUCTILITY DAMAGE CRITERION OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT

In this paper, drawbacks of present damage criteria of RC structures are figured out. As seismic response of a structure is a vibrating process, structural damage/failure should be considered in this process. Low-cycle fatigue tests of twenty 1/2-scale RC specimens were undertaken to obtain fatigue life curve for RC columns. On the basis of experimental results, equivalent ductility damage criterion is proposed. Efficiency of the criterion is verified by means of simulation tests on RC columns inputing real seismic waves.

KEYWORDS

Equivalent ductility; cumulative damage; fatigue life curve; damage criteria; dissipated energy.

INTRODUCTION

Structural failure under seismic excitations generally falls into two categories: first excursion and cumulative damage. Seismic response of a structure is usually a process of vibration unless it is extremely weak or/and the input earthquake magnitude is unusually great, which may lead to severe damage or total collapse of the structure just in a single pulse. Therefore, damage or failure assessment of the structure or its local components should be carried out according to its performance in the process of earthquake-induced vibration.

In engineering practice, ductility is usually used to evaluate structural damage or failure after yielding. However, the concept of ductility does not, or at any rate not fully, unveil a structure's vibrating characteristics and its rules of stiffness degradation and strength deterioration. Experiments have shown (Liu, 1994) that structural damage development accompanies stiffness degradation and strentgh deterioration almost at the same time. For this reason, stiffness degradation criteria (damage ratio) (Banon and Biggs, 1981) or strength deterioration criteria (Li and Cheng, 1993) reflect to same extent the crux of structural damage. Although rules of stiffness degradation and strength deterioration are readily qualitatively available, it is difficult to describe them quantitatively (Liu, 1994).

Park and Ang (1985a, b) introduced a damage function for seismic damage assessment that includes both maximum deformation and cumulative dissipated energy, which is expressed as

$$D = \frac{\delta_{max}}{\delta_u} + \frac{\beta}{Q_y \cdot \delta_u}\int dE, \tag{1}$$

where δ_{max} is maximum deformation, δ_u is ultimate deformation under static monolithic loading, Q_y is yielding strength, β is a non-negative factor dependtent on several structural parameters, $\int dE$ is total dissipated energy, D is damage index. The damage function expression shows such a viewpoint for certain that under seismic loading, RC structures are generally damaged by a combination of stress reversals and high displacement excursions. However, the chief drawback of the above-mentioned expression is that it can not correctly account for effect of the number of displacement cyclic loops on cumulative damage when a member is in vibration. According to eq. (1), a structural member cyclically loaded at one peak displacement could dissipate the same quantity of seismic energy as the one firstly cyclically loaded at the same peak displacement and then loaded at a much smaller displacement amplitude. But the experimental results have shown (Liu, 1994) that the dissipated energy when structural failure occurs under such conditions is strongly dependent on loading path.

Structural response under earthquake loading is a process of vibration. In this vibrating process, whether a ductile RC structure fails depends on cumulative damage development in its critical regions under cyclic displacements which are various in magnitude. It is believed that the relation between displacement and rate of cumulative damage development, that is, the relation between loaded displacement and fatigue life of a component, can be acquired on the basis of low-cyclic fatique experiments of RC columns under different displacement amplitude after yielding. It is further recognized that this kind of relationship can be found out by equal-amplitude and unequal-amplitude cyclic displacement loading on RC columns to allow for such common phases as different positive/negative and different backward/forward displacement amplitude. An expression of damage increment corresponding to each peak displacement thus can be obtained in such displacement reversals. Based on the expression, final cumulated damage in structural critical regions can be figured out to decide whether structural failure occurs in these regions.

LOW—CYCLE FATIGUE LIFE OF RC COLUMNS

Experimental Results

The specimens represent columns in the weaker story of a RC frame. Geometric similitude coefficient is about 1 : 2. Detailing and loading condition are shown in Fig. 1. The specimen is hinged at two ends and horizontal loading acts at the mid-height. 8 specimens with the same section and detailing under symmetric displacement reversals after yielding, that is, displacement ductility in the positive direction is the same as that in the negative direction, are carried out. Shear-span ratio of the specimens is $\lambda=5.12$; axial compression ratio (ratio of actural axial force to product of sectional area multipling axial compression strength) is 0.23. The material properties and the main test results are summarized in Table 1.

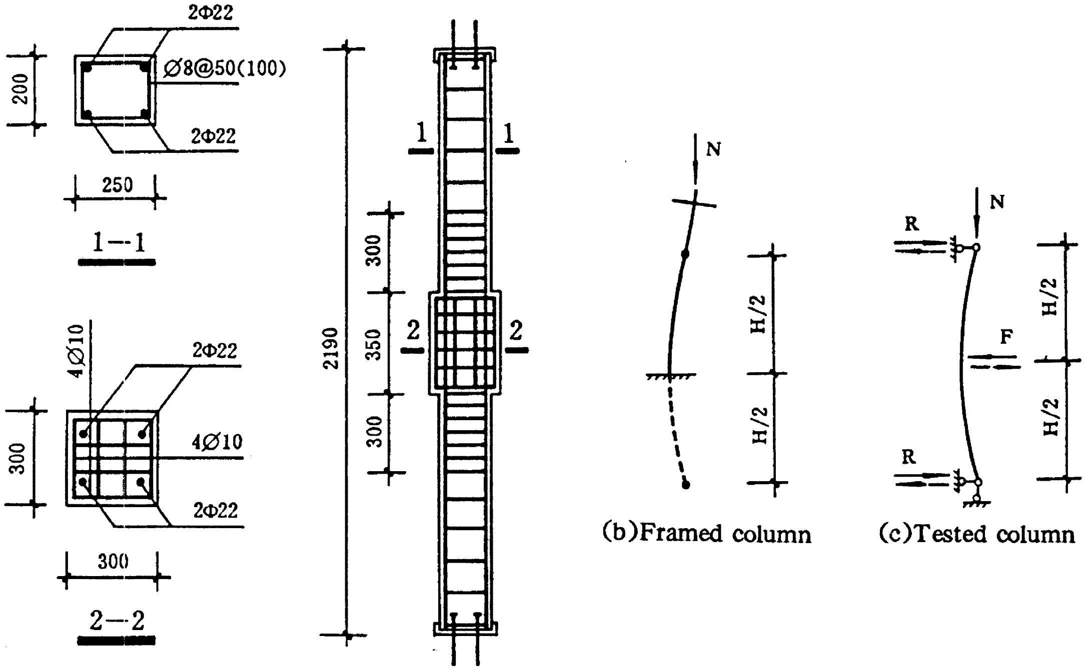
Low-Cycle Fatigue Life of RC Columns

It is observed from the above experimental results that cyclic numbers as failure of specimens occurs decreases rapidly when displacement amplitude increases. Intrinsic relationship between them thus can be concluded. Here fatigue life curve in metal fatigue theory is introduced to describe the relationship. If X-axis represents cyclic numbers N, and Y-axis stands for ductility μ, both coordinate axes are logarithmic, then the relationship between them can be shown in Fig. 2, which is expressed in best-fit form as follows:

$$\mu N^{0.182} = 4.45, \tag{2}$$

or

$$\mu N^{6.5} = 1.65 \times 10^{4}, \tag{2a}$$



(b)Framed column (c)Tested column

(a)Test specimen

Fig. 1 Detailing and loading system of tested columns

Table 1. Basic Parameters and experimental results

Specimen No.	f_{cu150} (N/mm²)	f_y (N/mm²)	f_u (N/mm²)	Horizontal Force(kN)		Yielding Displ. (mm)		Ultimate Controlling Displ. (mm)		Cyclic Loops
				p^{+}	p^{-}	$\Delta y^{(+)}$	$\Delta y^{(-)}$	Δ^{+}	Δ^{-}	
CF—3*	30.6	411.5	577.2	115.0 (125.0)		12.6		128.2 (77.0)		0.25
CF—1	33.3	411.5	577.2	135.0	114.0	15.5	13.5	31.0	27.0	268
CF—2	35.8	411.5	577.2	120.0	120.0	13.0	15.0	39.0	45.0	7.5
CF—4	39.0	411.5	577.2	133.0	121.0	14.4	14.4	57.4	57.4	2
CF—5	37.7	411.5	577.2	133.0	126.0	14.0	14.0	14→28	—14→28	1000 +66
CF—6	38.4	411.5	577.2	125.0	133.0	13.6	14.0	34.0	35.0	13
CF—7	36.6	411.5	577.2	125.0	120.0	13.9	14.2	20.9	21.3	1048
CF—14	42.0	374.9	560.1	118.0	120.0	12.5	12.5	12.5 25.0	12.5 25.0	7000 104
CF—20	44.9	374.9	560.1	12.0	123.1	11.5	12.5	25.9	28.1	135

Notes: * ——Monolithic loading. The horizontal force outside parenthesis is the yielding force, inside is the ultimate force; The ultimate controlling displacement outside parentheses is actural maximum displacement, inside is the displacement when the horizontal force is reduced to 0.85 maximum horizontal force.

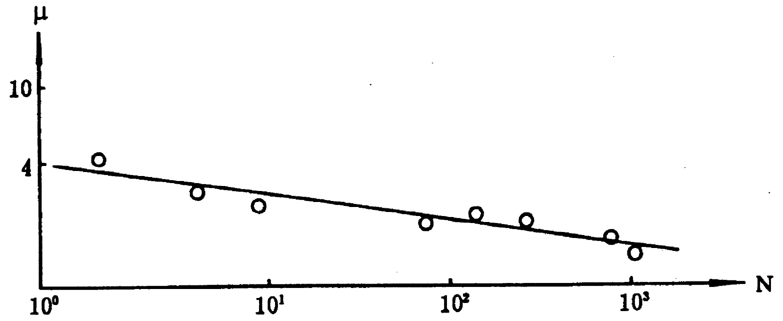


Fig. 2. Measured results and best-fit curve for relationship of displacement amplitude and fatigue life of columns

EQUIVALENT DUCTILITY DAMAGE CRITERION OF RC STRUCTURES

Based on the above analytical and experimental studies, it is recognized that the threshold of cumulative damage of RC structures subjected to displacement reversals, arraying in random sequence and changing in alternate direction and varying magnitude, depends not only on the peak response but also on each repsonse cycle and its sequence. As earthquakes last only in some seconds and structural foundamental periods are usually greater than 0. 1 second, structural failure in essence can be therefore treated as a problem of low-cycle fatigue whose cyclic numbers range in hundreds. For this reason, fatigue life curve is introduced in the evaluation of seismic damage criteria to account for characteristics of such low-cycle fatigue failure.

Equivalent Cyclic Number of Hysteretic loops

Time history of displacements under seismic excitations is a random process with the displacement amplitude varying. If a structure undertakes n_i and n_j times of equal displacement reversals while ductility levels are μ_i and μ_j respectively, and in the meantime, $\overline{N}_i$, $\overline{N}_j$ are fatigue life of the structure with the same ductility levels, that is, cyclic numbers up to structural failure, it can be reasonablely assumed that when $n_i/N_i=n_j/N_j$, damage of the structure (or component) is the same, thus

$$N_i = (n_i/n_j)N_j, \tag{3}$$

according to eq. (2) and eq. (2a), fatigue life curve can be expressed as

$$\mu_i N_i^{\beta} = \text{Constant}, \tag{4}$$

then

$$\mu_i N_i^{\beta} = \mu_j N_j^{\beta}. \tag{5}$$

Substituting eq. (3) into eq. (5) yields

$$n_i = (\mu_j/\mu_i)^{1/\beta} \cdot n_j. \tag{6}$$

That is to say, using eq. (6), n_j times of equal amplitude displacement reversals under ductility level μ_j can be equalized as n_i times of that under ductility level μ_i. If it is equalized under ultimate ductility level μ_p, then the equivalent cyclic number $\overline{N}$ will be

$$\overline{N} = \Sigma[(\mu_p/\mu_i)^{1/\beta} \cdot N_P] \tag{7}$$

Where N_P is fatigue life under ultimate ductility μ_p (cyclic numbers when failure occurs).

Damage Criterion Expressed by Equivalent Ductility

From eq. (5) equivalent ductility μ^* can be obtained as

$$\mu^* = \overline{N}^{-\beta} \cdot N_p^{\beta} \cdot \mu_P \tag{8}$$

Considering $N_P = 1/4$, when ultimate ductility μ_p is reached, then

$$\mu^* = (4\overline{N})^{-\beta} \cdot \mu_p = K\mu_p \tag{9}$$

in which, μ^*——Equivalent story-based ductility factor taking low-cycle fatigue into consideration, or abbreviated as equivalent ductility;

K——Equivalent factor, $K = (4\overline{N})^{-\beta}$;

μ_p——Ultimate ductility, story-based utimate ductility of a structure under monolithic loading;

β——Non-negative constant determined by low-cycle fatigue experiments. For RC structures, $\beta = 0.152$;

$\overline{N}$——Equivalent cyclic number, $\overline{N} = \sum_i n_i(\mu_i/\mu_p)^{1/\beta}$, n_i is cyclic number under ductility level μ_i.

For the sake of engineering convenience, damage index D is expressed as

$$D = \mu_{max}/\mu^* \tag{10}$$

Where μ_{max} is maximum displacement ratio subjected to earthquakes, $\mu_{max} = \Delta_{max}/\Delta_y$. $D = 0$ means no damage occurs in the structure, while $D \geqslant 1$, the structure is completely failed or collapsed. As for D ranging from 0 to 1, corresponding structural damage level can be tentatively classified as Table 2 by the abovementioned experiments while sufficient data is not available.

Table 2. Damage index D of various damage levels

Safe	Lightly Damaged	Moderately Damaged	Critically Damaged	Collapsed
0~0. 10	0. 11~0. 30	0. 31~0. 60	0. 65~0. 85	0. 86~1. 0

EXPERIMENTAL VERIFICATION

For the purpose of verification of the proposed damage criterion expressed in eq. (9) and eq. (10), substructure pseudodynamic tests of RC columns were carried out, employing computed time history of displacements. Section size and detailing are the same as the specimens in fatigue tests. Test results are summerized in table 3.

Table 3. Test results

Specimen	Max. Displ. ,X_{max} (mm)	$\mu = X_{max}/X_y$	Damage Index D at Max. Displ.	Damage Index D at failure	Input seismic waves
CF—17	—57. 42	4. 59	0. 58	1. 32	EL—Centro
CF—18	—69. 31	5. 54	0. 72	1. 36	Synthetic Waves
CF—19	88. 25	7. 06	0. 84	1. 18	Tianjin Wave

Experimental results of the three typical specimens have shown that although the displacement responses in the first several reversals do not reach the maximum value, serious cumulative damage occurs in the structure because of the large plastic deformation. In this case, it is inappropriate to evaluate damage or failure of the structure by means of maximum displacement reached afterwards.

Incorrect damage assessment of a structure or a component would be made if only the maximum displacement is considered and the second largest displacement and so forth are neglected. Equivalent damage criterion expressed in eq. (9), eq. (10) has been verified taking advantage of experimental results. It is shown that this criterion generally describes actural damage and failure mechanism of a structure/component and is of application value for rational and accurate decision on structural failure.

CONCLUSIONS

①As seismic response of a structure is a vibrating process, structural damage/failure should be considered in the process. ②Equivalent number of hysteretic loops is employed to account for cumulative damage effect in the proposed equivalent ductility criterion, integrating first excursion and cumulative damage in one single expression. Workability of the criterion in practical engineering is efficient. ③Damage of RC substructural components subjected to three kinds of seismic displacement time histories has shown that the proposed damage criterion describes seismic damage/failure mechanism more accurately and convincingly. It is of substantial value in evaluating structural damage levels of RC structures.

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