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EQUIVALENT DUCTILITY DAMAGE CRITERION OF EARTHQUAKE RESISTANT STRUCTURES AND ITS VERIFICATION BY SUB-STRUCTURE METHOD

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SUMMARY

Based on the analytical and experimental results, the equivalent ductility damage criteria is proposed in the paper. The low-cycle fatigue characteristics of structures are studied. The criteria also integrate first passage failure with cumulative damage failure and it's with a clear definition, simple form and good actual operational value during the engineering practice. In addition, it is related to the ductility which engineers have been familiar with. By means of sub-structure method, inputting displacement response curves relative to three kinds of ground motion, tests of three RC columns are carried out to verify the criteria

INTRODUCTION

Structural response under earthquake loading is a process of vibration. In this vibrating process, whether a ductile RC structure fails depends on cumulative development in its critical regions under cyclic displacement that is various in magnitude. It is believed that the relationship between loaded displacement and fatigue life of a component can be acquired on the basis of low-cyclic fatigue 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 regions can be figured out to decide whether structural failure occurs in these regions.

EQUIVALENT DUCTILITY DAMAGE CRITERION OF STRUCTURES

Based on the analytical and experimental studies, it is recognized that the threshold of damage of RC structures subjected to displacement reversals, arraying in random sequence and changing in alternate direction and varying magnitude, depends not on the peak response but also on each response cycle and its sequence. As earthquakes last only in some seconds and structure periods are usually greater than 0.1 second, structure 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.

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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, so it can be reasonably assumed that when $n_i / N_i = n_j / N_j$, damage of the structure (or component) is the same, thus

$$N_i = (n_i / n_j) N_j \tag{1}$$

According to the experimental results(Boquan LIU, 1994),low-cycle fatigue life of RC columns can be expressed as follows:

$$\mu_i N_i^{\beta} = Cons\tan t \tag{2}$$

Then

$$\mu_i N_i^{\beta} = \mu_j N_j^{\beta} \tag{3}$$

Substituting eq.(1) into eq.(3) yields

$$n_i = (\mu_j / \mu_i)^{1/\beta} . n_j \tag{4}$$

That is to say, using eq. (4), n_j times of equal amplitude displacement reversals under ductility level μ_j can be equalized as n_i times under ductility level μ_i. If it is equalized under ultimate ductility level μ_p, then the equivalent cyclic number $\overline{N}$ will be

$$\overline{N} = \sum [(\mu_p / \mu_i)^{1/\beta} N_p] \tag{5}$$

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

2.2 Damage Criterion Expressed by Equivalent Ductility

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

$$\mu^* = \overline{N}^{-\beta} . N_p^{\beta} . \mu_p \tag{6}$$

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

$$\mu^* = (4\overline{N})^{-\beta} . \mu_p \tag{7}$$

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 ultimate of a structure under monolithic loading;

β ----- Non-negative constant determined by low-cycle fatigue experiments. For RC structures, β=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

$$D = \mu_{\max} / \mu^* \tag{8}$$

Where $\mu_{\max}$ is maximum displacement ratio subjected to earthquakes, $\mu_{\max} = \Delta_{\max} / \Delta_y$. D=0 means no damage occurs in the structure, while $D \geq 1$, the structure is completely failed or collapsed.

PSEUDOSTATIC TESTING BU SUB-STRUCTURE METHOD

In order to test the structural earthquake damage criterion expressed by equation (7) and (8), this paper undertook the pseudo-static testing. In the test, three sub-structures---three RC columns is subjected to displacement history which is related to specific earthquakes.

Sub-structural Experiment Design

The experiment of the whole structural model is usually expensive and need special large-scale testing equipment. When the research interest lies in the partial function of the key section, the testing of the structural parts or composite parts will be more effective. For example, a simple two-story single span frame usually can be idealized as that there's a level horizontal freedom on every floor. If mainly interested in the reaction of the bottom column, we can only take out the bottom column as the experimental sub-structure and at the same time, consider the rest of the entire structure as the "analytical sub-structure"(fig. 1). This is so-called " sub-structure method". In order to further make this simple, we hypothesize that the position of in-flexure point of the bottom column is unchangeable, what is needed is only the testing of lower section of the column below in-flexure point of the bottom column. During the designing the experiment, the stiffness of the experimental sub-structure is intentionally made relatively weak while presupposing that it's damage index D>1, so as to make it turn into the evident non-lineal condition during the earthquake and become the key parts of controlling the structural damage.

What test specimens CF-17, CF-18 and CF-19 imitate is the bottom column of the 8-floor single span frame. The distance between the frame columns is 4.5m with span of 7.2m. The load is taken from general civil buildings. The size of this model is one second of its original one. The size of the testing column and corresponding steel usage are the same. The condition of loading and detailing of the specimens is referred to Liu's Ph.D thesis (Liu, 1994).

Structural Analytical Model and Restoring Force Model of the Structural Component

The analytical model of the structural dynamics uses the story shear type while hypothesizing that the stiffness of the level beam is infinite; The restoring force of the column uses the degenerated double-line model and the testing result of the reference (LIU,1994) to decide the story stiffness of the sub-structure.

Inputted Earthquake Waves and Displacement Response Curves of Sub-structure

According to the subordinate structure of CF-17, CF-18 and CF-19, we input El Centro wave, artificial time-history of ground motion and Tian Jin (China) wave with its maximum acceleration as 300 cm/s^2 . Considering that loading speed is very low the damping ratio is taken as zero. Using the Wilson-θ method ,we get the displacement time-histories of in-flexure point of the bottom column of the analytical structure (Fig. 2 as example) .

The Analysis of The Testing Results

During the experiment, inputting the displacement time-histories of in-flexure point of the bottom column by dynamic analysis , we get the hysteresis curves of the bottom column (example as Fig.3).

The experiment demonstrates that although CF-17 has not reached the ultimate ductility at its displacement amplitude (when damage index D is 0.58 based on the equation (9)), the testing sub-structure was eventually destroyed because of the accumulated damage during the recycling process ever since (D is 1.32 when it reaches 10 second).

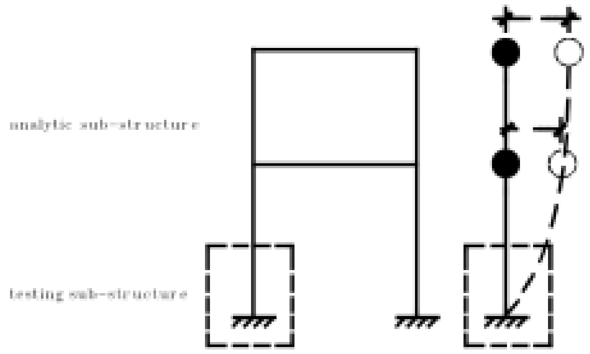

Figure 1: Analytical sub-structure and testing sub-structure

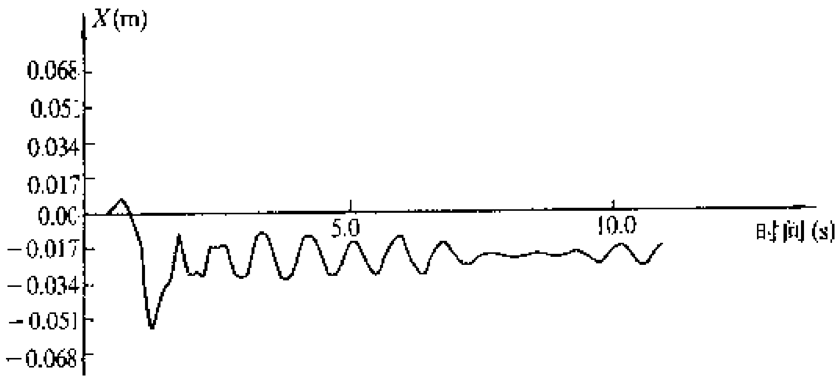

Figure 2: Displacement curve loaded to sub-structure CF-17(El-Centro wave)

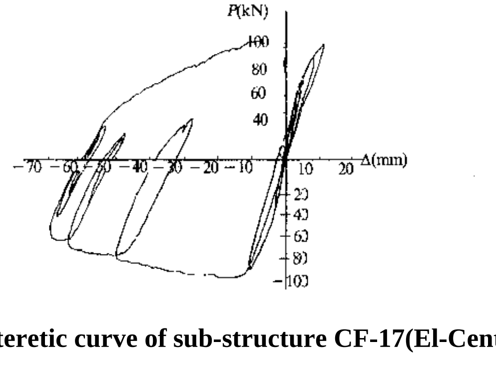

Figure 3 : Hysteretic curve of sub-structure CF-17(El-Centro wave)

The maximum displacement amplitude of CF-18 took place at 9.78 second (with μ_{max} =5.5), but the testing sub-structure has been severely damaged because of the effect of the several previous big displacement amplitude. It's unreasonable if the damage is evaluated only by using ultimate ductility. The damage index D is 1.36 when loading to 11.04 second and the testing column cannot maintain its vertical load during its process of resuming to its former balanced position.

CF-19 has been damaged seriously when it reaches its maximum displacement amplitude on two opposite directions (μ_{max} =7.06), but it still can maintain the vertical load with the relatively small decrease in its stiffness. When the testing sub-structure is continuously input displacement time-history, the concrete of the core section at 4.4 second is crushing, and the machine is shut down when they're added loading on the opposite direction because the vertical load dropped seriously and the stiffness degenerated too much. The damage index at this time is 1.18.

The three typical experiments can amply demonstrate that although the several previous displacement response has not reached the ultimate ductility, the structure has gone into the plastic phase so deeply that it has already accumulated severe damages before it reached its ultimate ductility. It's obviously unreasonable to evaluate the structural damage condition using the later maximum displacement response. If only considering the former maximum displacement and not the effect of later sub-maximum displacement, we could give false judgement of the structural damage and falling down. This experiment confirms equivalent ductility damage criterion expressed by the equation (7) and (8) and demonstrates that this criterion basically shows the actual damage function of the structural parts and have the practical value of reasonably and correctly judging the structural damage.

CONCLUSIONS

This paper presented that, the structural earthquake damage criterion expressed by the form of equivalent ductility considered the accumulated effect of the structural damage by equivalent cyclic number and make the first excursion and the cumulative damage united in the single equation with a clear definition, simple form and good actual operational value during the engineering practice .

The damage of the experimental sub-structure pit in three different displacement time-history of ground demonstrates that the damage principle presented by this paper shows the earthquake damage function and has practical value of reasonably judging the structural damage and falling down. The damage index concluded from this criterion is slightly safe. As far as such large dispersed material as concrete, the conclusion should be believed to be convincible

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