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Damage and reserve capacity evaluation of structures subjected to strong earthquake ground motion

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ABSTRACT: A key component in the design of structures to resist strong earthquake ground motion is the proper evaluation of the degree of damage induced by strong shaking. Typical building codes utilize some form of implicit or explicit ductility factor, thought to provide some measure of deformational damage, that in turn is used to reduce the design forces. These factors are based solely on the structural system. The problem is that these factors, and even the concept of ductility itself, in its classical form is limited to only the maximum response and ignores damage caused within the limiting response value.

This paper addresses new "first order" techniques that aid in our ability to determine the deformational damage levels, and reserve capacity, caused by strong ground motion. Energy and fatigue-based methods are used to define damage. The results show that ductilities must be limited to modest levels, 3-4, so as to avoid serious damage to structural systems and to internal mechanical equipment.

1 INTRODUCTION

Structural design to resist earthquake ground motion is a difficult problem. The earthquake motion is not known before hand and thus the designer must rely on expert opinion, the historical record and relevant building codes to guide the process of defining the earthquake hazard. Once this "design" earthquake is defined, some form of analysis can be performed to determine the adequacy of the structure under the seismic loading. This analysis can be in the form of a static or a dynamic calculation of the lateral forces acting on the structure.

In most building codes the prescribed lateral forces are computed in terms of a seismic base shear determined through a pseudo-static representation of the ground motion. This shear is based on the seismic zone factor, structural importance, weight, period and soil characteristics. Once determined, the base shear can then be distributed across the various floors to be used for evaluation and/or design of the structural elements. One key ingredient in the process is the reduction of the "true" seismic forces to a design level through application of a response modification factor. This reduction takes advantage of the ability of a well designed and well detailed structure to undergo controlled levels of nonlinearity without compromising structural safety. Even so, a lack of consistency between force and deformation levels normally exists, as will be discussed.

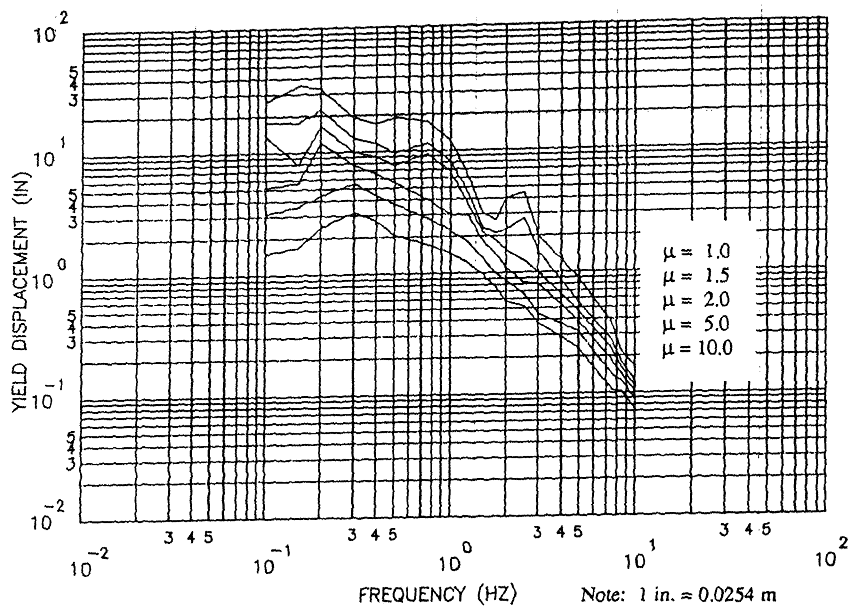
These response factors can range from near one for unreinforced masonry to ten or more for ductile frame systems. The question that arises is how accurate is this representation of seismic demand on a system? Can the designer really capture the damage caused by dynamic response to strong ground motion in terms of a single parameter, one based solely on the structural system?

This paper addresses the concept of damage is light of research conducted by the authors over the past decade. New analytical methods, and concepts, will be applied to explore this question. The predicted damage using traditional techniques will be compared to the results from these new approaches. What emerges is a conclusion that excessive levels of nonlinearity may well cause more damage than first thought and should be avoided.

2 THE DAMAGE CONCEPT

Evaluation of structural response from earthquake ground motion has long been established in terms of the maximum displacement and force that is anticipated. In the case of linear response, displacement and force are directly tied together through the structural stiffness.

Under nonlinear response, structural displacement and force levels are no longer directly related. Nonlinearity changes the stiffness and, thus, force and displacement are not uniquely related. Traditionally the ductility factor, the ratio of maximum displacement to the yield displacement, is used to depict the degree of nonlinearity, and the damage. Ductility works well for damage evaluation under noncyclic, monotonic loading because it does represent the maximum response, or the envelope, of the demand in the structure. Indeed the



Note: 1 in. = 0.0254 m

Fig. 1 Yield displacement spectrum for a 5% damped structure responding to Pacoima Dam to specified maximum ductilities

ductility factor was developed to describe damage from explosions, which tend to load structures in a dynamic but monotonic manner.

Ductility was adopted for use in earthquake damage evaluation because of its successful use in monotonic applications. It has been used as a basis for determining response spectra based on prescribed levels of nonlinear maximum response. As illustrated in Fig. 1, yield displacements can be adjusted accordingly to provide a maximum ductility corresponding to the desired value. Design spectra also can be constructed readily based on the ductility factor, Newmark and Hall (1982).

The ductility factor in turn has spawned the response modification factors used in building codes. These factors are based on the competency of the various structural systems and are used to reduce the forces applied in design, based on an assumed level of nonlinear behavior and indirectly, energy absorption. Once the system is determined to resist these reduced seismic forces successfully, the resulting drift is then checked to ensure that excessive lateral movement does not occur. There is no direct computational tie between the seismic forces and the drift except through the check on the drift. Thus, an acceptable structural system from an equilibrium viewpoint may fail the drift limit, typically 0.5 to 1.5 percent of the story height. In other forms of structural analysis and design, force and displacement are directly related and can both be checked in one calculation; such is not the case in seismic design under present rules.

Also it is important to note that the reduced forces are distributed through the structural system based on the elastic stiffnesses of the various members and connections. The act of developing partially plastic hinges, preferably in girders, destroys this elastic distribution. Thus, the force distribution may not follow that based on the initial stiffnesses, rather loads will flow into the stiffer elements at the base of the structure and hinges will develop here and will then propagate upward through the structure. Some members, those in the upper areas of the structure, may never become nonlinear while those near the bottom may "see" demands significantly different than those envisioned in design. In short, an unbalanced pattern of yielding and energy absorption may occur.

One may ask, why is this important to note? The prescribed force reduction factors are based on an assumed level of ductility. If this ductility level is not reached through a difference in structural response or load path through the system, then the actual forces in the elements may exceed those employed in design. Therefore, there is one and only one value of nonlinear response/ductility, that makes the reduced force match the actual demand. This fact is not well understood by many in practice. The chances of achieving this nonlinearity are obviously impossible to compute a priori. However, damage evaluation requires careful calculation of the actual structural deterioration caused by ground motion. Clearly, response factors applied based on structural system alone introduce an additional level of uncertainty and probably should not be used with a high degree of confidence.

The point here is that the response factor is based solely on the structural system and its relative ability to resist damage from earthquake. The ductility factor, in contrast, was developed based on the cause and effect relationship between the particular earthquake and the structural yield displacement required to induce the desired level of nonlinearity. The ductility factor directly acts to change the yield displacement based on calculated response, and thus indirectly acts to reduce the design force levels. Use of a response modification factor mimics the effect of the ductility factor in that it also acts to reduce forces. However, the response factor works in the opposite fashion and directly acts on forces. One may ask how accurately designers check the yield displacements in their systems to insure that the computed ductility matches the assumed -- the answer is they normally do not do so. The level of nonlinearity is in reality an unknown in terms of ductility, or any other measure. The designer trusts the codes and hopes that a properly sized and detailed system will behave as designed; thus the actual damage level may not be directly addressed by typical code-based approaches.

The designer performing a response spectrum analysis can do an improved job of predicting structural response over pseudo-static methods since a dynamic analysis procedure is employed. However, the analysis is still based on an elastic structure that fails to exist after the plastic hinges form. The assignment of a ductility factor to produce a reduced level for design purposes may more correctly address nonlinearity than a response modification factor does. However, the spectrum does not enable the designer to evaluate the effects of the nonmaximum cycles of response. Intuitively, all of the cycles of nonlinear response should cause damage, yet the nonlinear response spectrum predicts the same "damage" for a ductility of say, five if this ductility is reached once or fifty times.

Based on the foregoing, new and improved means of damage evaluation are needed. The following discussion addresses a promising area that may suggest a basis for needed improvements in damage evaluation.

3 NEW CONCEPTS IN DAMAGE EVALUATION

If one is going to assess damage under repeated deformation cycles, then a technique must be developed to account for damage accumulated during this response. Importantly, such a technique should address the entire response history, not just a maximum value of response.

One such technique involves evaluation of the response energy in terms of strain, hysteretic, kinetic and damping energies. The basic equation of motion for base excitation is

$$m\ddot{u}+c\dot{u}+ku = -m\ddot{y} \qquad (1)$$

where m is the structural mass, c is the damping, k is the stiffness. The terms $\ddot{u}$, $\dot{u}$ and u represent the relative acceleration, velocity and displacement of the mass to the ground; y is the ground acceleration at any time. Integrating Eq. 1 over the displacement results in a form that can be readily evaluated for energy contributions along with the individual response values, Zahrah and Hall (1984).

A typical response and energy time history is presented in Fig. 2. In this figure, it can be seen that the entire response is represented. The effects of all the cycles of response are represented. The hysteretic term includes the summation of the energy contained inside the hysteresis loops. This term is directly related to the

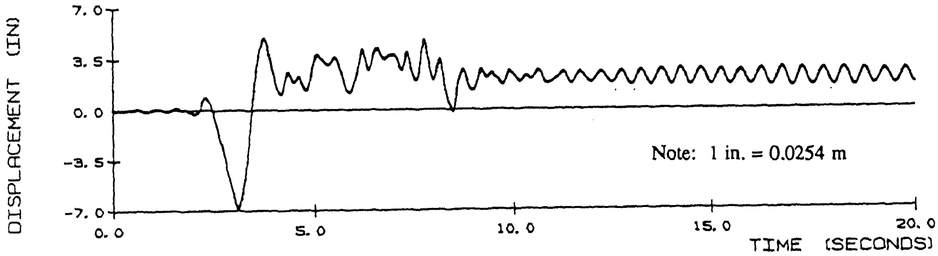


Fig. 2a Relative displacement time history for a 2hz undamped structure responding to Pacoima Dam

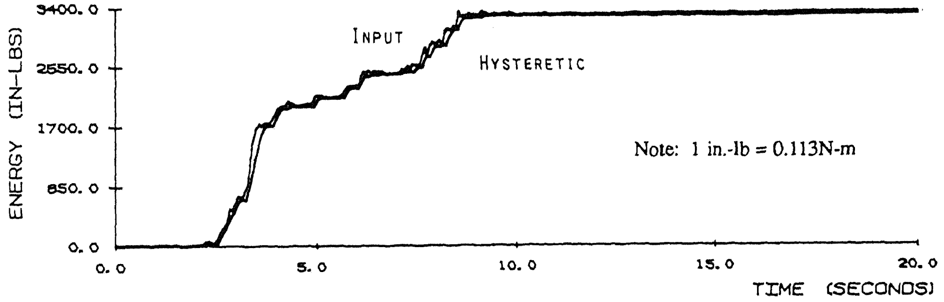


Fig. 2b Energy time history for a 2hz undamped structure responding to Pacoima Dam

number of response cycles and the number of yield excursions; in short the hysteretic energy is directly related to the seismic demand placed on the element -- the damage -- and may be the best parameter for damage evaluation.

How can this parameter be used to evaluate damage? One day, designers may have allowable energy values for members and materials. Today, however, energy must be related to more conventional values of response.

McCabe and Hall (1989) observed that ductility, μ, is in fact comprised of two parts, an elastic ductility that ranges from zero to one and a plastic ductility, μ_p, that starts at zero. It is this plastic ductility that is responsible for damage under cyclic response. The question is how does the damage from a monotonic ductility, μ, applied once relate to a ductility that may be applied to the structure many times? The answer lies in the application of low-cycle fatigue concepts to determine the hysteretic plastic ductility, μ^*, that is responsible for damage generation. Using low-cycle fatigue concepts, the effect of repeated cycles of response can be found as

$$\mu^* = \mu_p (2N)^{-0.6} \tag{2}$$

This concept is based largely on Morrow's low-cycle fatigue model, Morrow (1965). Here μ^* is the hysteretic plastic ductility, μ_p is the plastic ductility allowed under monotonic loading and 2N is the number of reversals; there are two load or direction reversals per cycle of response. The exponent of -0.6 is typical for structural steels. The actual hysteretic energy can be computed and compared against the permitted amount of hysteretic energy based on complete damage or

$$H_t = \mu^* R_y U_y (2N_f) \tag{3}$$

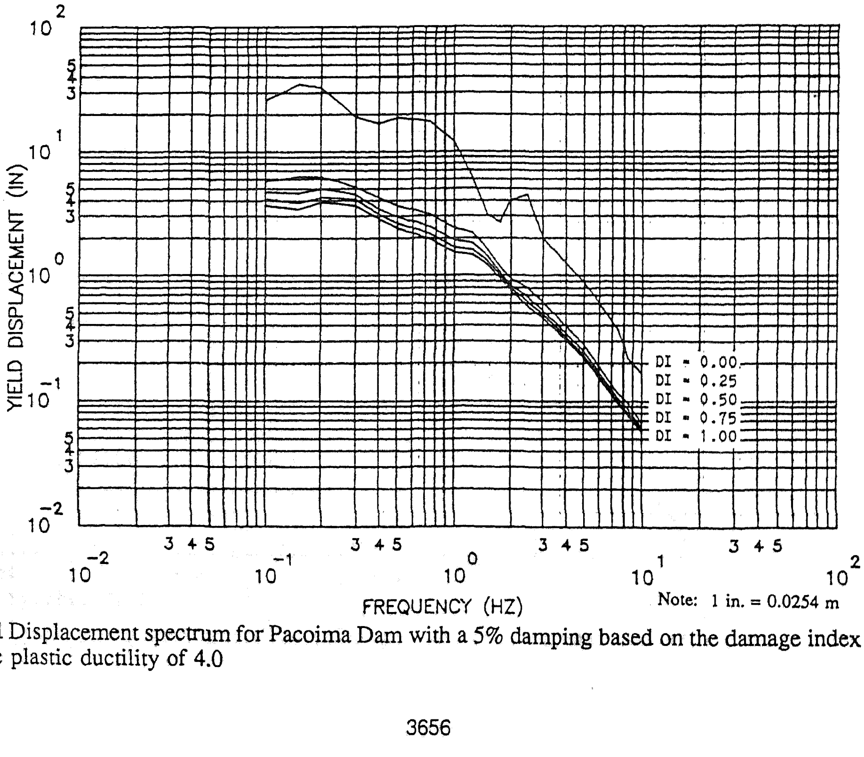
where R_y and U_y are the yield resistance and displacement values and $2N_f$ are the number of reversals to failure, based on an elastoplastic material model. This value can then be compared against the actual hysteretic energy values to determine the degree of damage. A damage index, DI, based on a quadratic energy dissipation law, was used as one example of the application of this technique, McCabe and Hall (1989),

$$DI = \left(\frac{H_p + H_n}{H_t}\right)^2 + \left(\frac{H_p - H_n}{H_t}\right)^2 \tag{4}$$

where H_p is the energy dissipated under the positive force portion of the hysteresis loop and H_n is the energy dissipated over the negative force part of the hysteresis loop. The term H_t is computed from Eq. 3. The first term addresses the damage from the entire energy dissipation; the second term addresses damage from unequal energy dissipation. In fact, the amount of residual drift following response of an elastoplastic system can be computed based on the difference of H_p and H_n divided by the yield resistance. Values for DI range can range from 0.0 (elastic) to 1.0 (completely damaged) or more.

4 THE CASE TO LIMIT DUCTILITIES

The question of how large a ductility is too large for design can be addressed using the damage mechanics approach outlined above. In Fig. 3, a yield



Note: 1 in. = 0.0254 m

Fig 3. Yield Displacement spectrum for Pacoima Dam with a 5% damping based on the damage index with a monotonic plastic ductility of 4.0

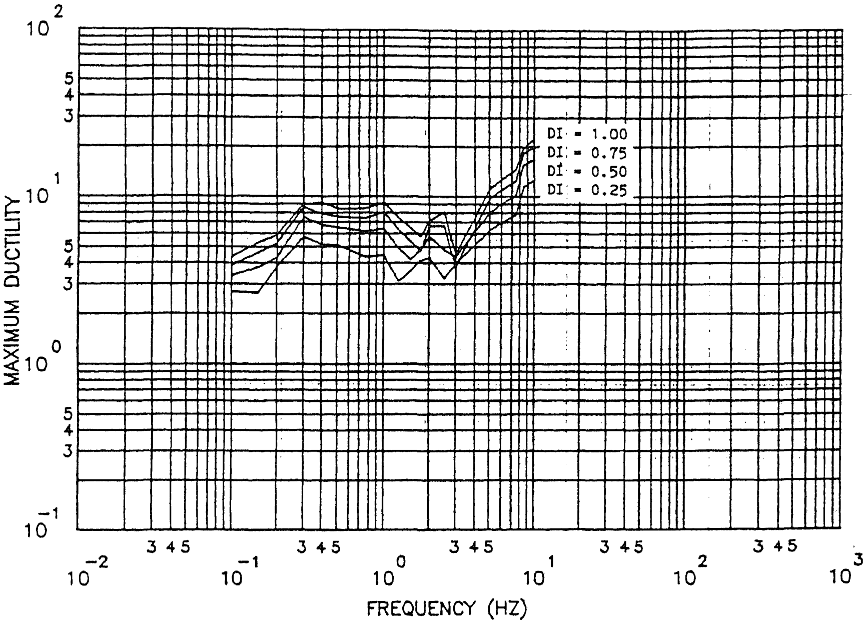


Fig 4. Maximum ductility spectrum for Pacoima Dam with a 5% damping based on the damage index with a monotonic plastic ductility of 4.0

displacement spectrum is presented based on this concept. It can be seen that the curves are smooth and regular, because the calculation includes all of the record, not just a single point of maximum response. Comparison with Fig. 1 reveals that this procedure requires yield displacements that are comparable to those for maximum ductilities of 3-5, and greater than that for a ductility of 10 -- all based on an allowable monotonic plastic ductility of 4, a value that can be attained by most structural members. Thus, reasonable maximum ductilities correspond to monotonic plastic ductilities that can be reasonably achieved in design. Perhaps more significantly is that the computed maximum ductility spectra, based on this Damage Index approach produces ductilities of between 3 and 10, based on a monotonic plastic ductility of 4, as shown in Fig. 4.

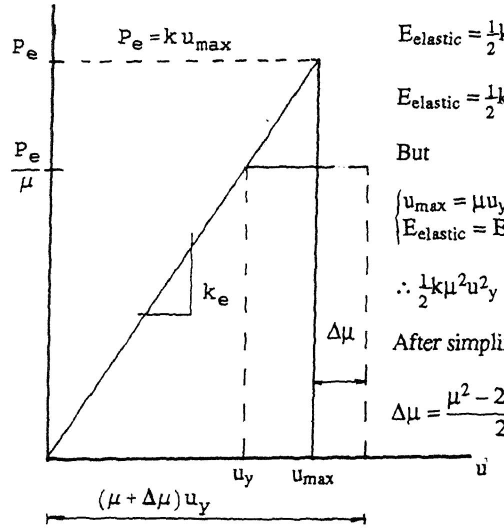
Stated another way, monotonic ductilities and hysteretic ductilities are not identical. What is known to cause complete damage under monotonic loading may cause more severe, or less severe, damage under hysteretic loading depending on the ground motion and the structural characteristics. What is clear is that designing and detailing a member to resist a ductility, defined in the classical sense, of 4 may result in some cases in an actual ductility of 10 in dynamic response. Moreover, repeated cyclic response to ductilities in excess of ten are difficult to sustain in a structure. Thus, the designer may be gambling with the survival of the structure if too large a ductility is assumed (especially if there is unbalanced yielding as discussed earlier) since the monotonic ductility can be amplified by the dynamic response, as is the damage.

Another illustration of the danger in the use of excessive ductility values in design follows. If it is assumed that 10 full cycles of response to a total ductility of 10 (a plastic ductility of 9) over each cycle are to be sustained, application of Eq. 2 reveals that the design monotonic plastic ductility would need to be

$$\begin{aligned} 9 &= \mu_p (2 \cdot 10)^{-0.6} \\ \therefore \mu_p &= 54.3 \end{aligned} \tag{5}$$

Thus, a total monotonic design ductility of just over 55 is required to match the damage sustained in the response with each cycle reaching a total ductility of 10. Few engineered structures are capable of such large ductility values -- yet these are required for consistent damage between monotonic ductility and hysteretic ductility. If the system were designed for a monotonic ductility of 10, then application of Eq. 2 reveals that a hysteretic plastic ductility of 1.49 results. This value represents the plastic ductility over each of 10 cycles that damages a member to the same extent as a monotonic plastic ductility of 9 (a total ductility of 10).

These results lead directly to the conclusion that large values of ductility, say 7 to 10, may not be realistically attained in structures that will survive repeated strong shaking. Or stated in other words, significant damage may result if the structure is designed on a classic ductility basis, which is effectively a monotonic concept. Coupled with the indirect scaling provided by the response modification factors on the forces, and the assumed elastic distribution on an admittedly inelastic system, one



$$E_{elastic} = \frac{1}{2}ku^2_{max}$$

$$E_{elastic} = \frac{1}{2}ku^2_y + ku_y(u_{max} - u_y) + ku_y(\Delta u)$$

But

$$\begin{cases} u_{max} = \mu u_y \\ E_{elastic} = E_{inelastic} \end{cases}$$

$$\therefore \frac{1}{2}k\mu^2u^2_y = \frac{1}{2}ku^2_y + ku^2_y(\mu - 1) + ku^2_y\Delta u$$

After simplification

$$\Delta\mu = \frac{\mu^2 - 2\mu + 1}{2}$$

Typical Results

μ	$\Delta\mu$
1.0	0
1.5	0.125
1.75	0.281
2.0	0.5
3.0	2.0
5.0	8.0
10.0	40.5

Fig. 5 Load-displacement curve showing the effects of increased ductility in energy absorption

becomes concerned with applying the large factors permitted by many codes.

One can argue this question of ductility from another aspect of the energy approach. Inelastic behavior is known to dissipate energy through the generation of hysteretic energy, the area inside the force-displacement curve. If the area under the elastic load-displacement curve is assumed to be a constant level of energy to be dissipated, as the ductility is increased the total amount of displacement must be increased so as to generate the same amount of energy under the curve. As shown in Fig. 5, the effect of increasing the ductility reduces the effectiveness of the system in generating energy. For small ductilities, values of about 5 or less, this effect is not large. However, at extreme values of ductility, this reduction in effectiveness, shown by the increased value of displacement required, is apparent.

A related question is the survival of any necessary mechanical equipment located inside the structure. The traditional view of building codes has been one of life safety. Loma Prieta showed that the economic losses from damage to building contents may be staggering and should also be considered in the design of structural systems. Designers must be aware that significant interruption of building operation may be as damaging in terms of lost income as the structural damage that they attempt to control. Thus, once again the prudent limit of nonlinear behavior to a controlled region just above one may be indicated based on equipment considerations as well.

5 CONCLUSIONS

New and more comprehensive methods are being developed to evaluate structures subjected to strong earthquake ground motion. Research by the authors has shown that energy and fatigue concepts can be combined to produce an effective way to view damage.

The results indicate that maximum ductilities may well need to be limited to lower values that first thought. Excessive damage can result from maximum ductilities that occur, damage that may not be uniform in the structure.

The entire subject of reduced force design needs careful thought. This need is particularly great if structures are to be rehabilitated after earthquakes and perhaps subjected to repeated damage over their lifetime. Moreover, Loma Prieta revealed the economic penalties that occur from equipment damage inside these structures. The authors believe that in time it will be possible to design structural systems, as well as equipment systems, on the basis of rational energy considerations. This paper reflects some of the conceptional thought being devoted to the subject.

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