SMiRT-12 / K. Kussmaul (Editor)

L10/2

EFFECTS OF DEAD LOAD ON DUCTILITY OF A FLOOR SYSTEM

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1. INTRODUCTION

In seismic margin or seismic fragility calculations, the ductility scale factor F_μ is often used to quantify the effect of inelastic energy absorption on structural capacity. In concept, the ductility scale factor can be thought of as a response spectrum reduction factor. For a given ductile structural element and input response spectrum, the product of F_μ and the factor of safety against yield (F_S) provides a measure of the total factor of safety against failure (F).

Testing and analytical studies by others have shown that structures such as shear walls and building frames (mounted vertically) subjected to horizontal input motions are capable of absorbing earthquake energy through inelastic behavior. Kennedy, 1984, Riddell, 1979, and Reed, 1991 studied the ductility scale factor and developed simplified procedures through the use of nonlinear analyses.

For floor systems (mounted horizontally), we are mainly interested in the response to vertical input motions. Because of the constant downward pull of gravity, the nonlinear displacement of a floor structure is biased downward. This ratcheting phenomenon reduces the ductility scale factor for a horizontal element compared to the case where the same element is mounted vertically and is subjected to horizontal input motion.

Through the use of nonlinear time history analyses, we investigated the effects of dead loads on the ductility scale factor of floor systems. We also developed a simple modification to the Riddell-Newmark procedure (Riddell, 1979), which is used to calculate the ductility scale factor for vertically mounted elements, to determine F_μ for horizontally mounted elements.

2. ANALYTIC MODEL

The vertical response of a floor system can usually be idealized as a single-degree-of-freedom system since its seismic response is predominantly due to the fundamental mode. Floor systems constructed of reinforced concrete or steel typically possess static strength capacities that are governed by ductile flexural behavior. In such cases, the element ductility μ is usually defined as the ratio of the achieved inelastic displacement (Δ_u) to the yield displacement (Δ_y).

A one-mass, one-spring model was used in the study. The spring's response was represented by a bi-linear force displacement curve with a small amount of strain-hardening to reflect the characteristics of both structural steel and reinforced concrete members. Tangent stiffness proportional damping with 7% elastic damping was used.

In the study, the model's spring stiffness was varied to achieve oscillator elastic frequencies of 4, 7, 10, and 20 Hz. The 4 and 7 Hz frequencies lie on the descending portion of the input motion response spectrum (Figure 1), while the 10 Hz frequency lies near the peak of the spectrum. The 20 Hz frequency lies between the "rigid" range and the peak of the spectrum.

A dead load equal to 30% of the spring's yield capacity was used for most analyses. A few analyses were made with a dead load of 60% of the spring's yield capacity to study the sensitivity of results to this parameter.

A Pacoima Dam vertical earthquake record and a Tabas vertical record, each modified to match a target spectral shape, were used in the study. Figure 1 shows the modified Pacoima Dam spectrum. Since the input motion is scaled up or down to achieve a range of element ductilities in the study, the absolute level of the input time history is not important.

3. ANALYSIS PROCEDURE AND RESULTS OF NONLINEAR ANALYSIS

Nonlinear analyses were performed using the DRAIN2D computer code (Kannan, 1973, revised, 1985). The bi-linear truss element was used to simulate the inelastic behavior of the structural member. A time step of 0.001 second was used for all computer runs.

For each model, the scale factor (F_s) applied to the input time history to just achieve yield of the spring was first determined from elastic analysis. A range of scale factors (F) exceeding F_s was then applied to the input time history and nonlinear analyses were performed. For each nonlinear analysis, the ductility scale factor F_μ was determined by definition, from F/F_s, and the corresponding maximum element ductility μ achieved was determined from the ratio of Δ_u/Δ_y. Tables 1 and 2 summarize the results of the nonlinear analyses using the modified Pacoima Dam record.

Scale factors F were selected to achieve element ductilities in the range of about 2 to 8. Although ductile floor systems in flexure can achieve ductilities well in excess of 8, equipment attached to the floor may be unable to tolerate the corresponding inelastic displacements. In such cases, the failure of the floor system should be defined by the limit state of excessive displacement instead of structural collapse.

In Figures 2 and 3, the displacement vs. time plots for cases with and without dead load illustrates the ratcheting phenomenon. Table 1 shows that for the same element ductility achieved, the ductility scale factor is reduced when dead loads are present compared to the case without dead loads. The following section will present adjustments to the element ductility for the effect of dead load.

4. DEVELOPMENT OF SIMPLIFIED PROCEDURE

Other investigators have developed simplified methods for estimating the ductility scale factor F_μ without the effect of ratcheting due to dead loads. These formulations have frequently used the element ductility (μ) as the key parameter. In our study, we used the method developed by Riddell and Newmark (Riddell, 1979), which is summarized below:

F_μ = Larger of $F_{\mu 1}$ or $F_{\mu 2}$

$F_{\mu 1}$ = Smaller of $F_{\mu 3}$ or $F_{\mu 4}$

In which $F_{\mu 2}$, $F_{\mu 3}$, and $F_{\mu 4}$ apply to different frequency ranges. For 7% damping, those values are given by the following expressions:

$F_{\mu 4} = [Sa(f)/ZPA]\mu^{0.11}$ Rigid Range

$F_{\mu 3} = (2.673\mu - 1.673)^{0.411}$ Amplified Acceleration Range

$F_{\mu 2} = C_f(2.240\mu - 1.240)^{0.611}$ Amplified Velocity Range

$C_f = f_k/f$ when $f_k/f < 1.0$ or $C_f = 1.0$ when $f_k/f \geq 1.0$

In which f_k is the "knuckle" frequency between the zone of approximately constant amplified spectral acceleration and the zone of approximately constant amplified spectral velocity.

To account for dead load, we modified the element ductility by considering two important effects.

Because of the dead load, the total work done by the spring is defined by the yield capacity minus the dead load force in the spring ($P_y - P_{dl}$) moving through the inelastic displacement. This first effect is equivalent to shifting the origin of coordinates of the force-displacement curve from its original location to the point where the force in the spring is equal to the dead load (point A in Figure 4). Effectively, the dead load makes the spring weaker and inelastic behavior more likely in the downward direction compared to the upward direction. From nonlinear analyses made with dead loads of 30% we found that only slight yielding occurred in the upward direction. Redefining the element ductility μ' as $(\Delta_u - \Delta_{dl})/(\Delta_y - \Delta_{dl})$ follows easily from this reasoning. Note that the conventional definition of element ductility $\mu = \Delta_u/\Delta_y$ is equivalent to μ' when no dead loads are applied.

The second effect deals with the cyclic nature of seismic loading. A floor structure with significant dead load is likely to dissipate energy inelastically in only the downward direction. Thus, the ductility achieved in a ratcheting cycle rather than the maximum total ductility achieved is of interest for calculating the ductility scale factor. In our study, we therefore computed an "effective" ductility from the redefined element ductility μ' to account for the cyclic nature of the seismic loading. The effective ductility was determined as follows:

$$\mu_e = 1 + (\mu' - 1)/n$$

Where:

μ' = Element ductility based on shifted origin of coordinates, defined above.
n = Adjustment factor to account for cyclic loading.
μ_e = Effective ductility that accounts for the effect of dead loads.

The value of "n" is related to the number of strong motion ratcheting cycles to which the structure is subjected. This factor may depend upon, among other variables, difference in available resistances in the upward vs. downward directions before yield (i.e., magnitude of dead load), duration of ground motion, and input time history of ground motion. Such an interpretation of n is illustrated in Figure 4. The predicted ductility scale factor was then computed by using the effective ductility in place of the element ductility in the Riddell-Newmark equations described above.

5. CONCLUSIONS

A comparison of the predicted F_μ values using the simplified method with a value of n = 5 and those computed from nonlinear analyses is shown in Table 2 for dead load equal to 30% of the yield strength of the spring. For the analysis cases considered, the ratio of the predicted F_μ to actual F_μ had a mean value of 0.995 and a coefficient of variation of 0.11. Similarly, for cases with a dead load equal to 60% of the yield capacity of the spring, the ratio of the predicted to actual F_μ had a mean value of 1.02 and a coefficient of variation of 0.13 when using a value of n = 6 (Table 2A). This implies that the value of n is apparently not greatly sensitive to variation of dead load in the given range.

Insensitivity to the dead load percentage should perhaps not be completely unexpected for the range considered in this study. We can see the reason for this conclusion by constructing the hypothetical force-displacement traces of models with dead loads equal to 30% and 60% Py, when each has achieved the same value of μ'. Since the springs become inelastic for these cases almost exclusively in the downward direction, the force-displacement trace for the dead load of 60% P_y case is virtually a scaled-down version of the trace for 30% P_y, when the second slope of the force-displacement curve is small (Figure 4). Note that the input motions used in these two cases have different scale factors. From this comparison, it seems reasonable that the value of n would not vary significantly for dead loads greater than 30% P_y. At some dead load percentage less than 30%, however, significant nonlinear behavior will occur in the upward direction. We would expect n to be more sensitive to dead load percentage in such a range.

For analyses made with the modified Tabas record, dead load of 30% P_y, and a value of n = 5, the mean ratio of predicted to actual F_μ was 1.07 with a coefficient of variation of 0.11.

When considering all the data described above, a value of n = 5.5 resulted in a mean ratio of the predicted to actual F_μ of 1.00 and a coefficient of variation of 0.11. This low variability is comparable to the results reported by Kennedy, 1984 and Riddell, 1979 for structures not subjected to the ratcheting phenomenon.

Because of the importance of ground motion variability on structural response, further work is needed to study the effects of different earthquake records on the ratcheting phenomenon. A range of values of the percentage of dead load should also be explored.

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Table 1. Comparison of ductility scale factor with and without dead load.

Case	Element ductility μ	F_μ, 4 Hz model	F_μ, 7 Hz model
No dead load	5	3.68	2.27
Dead load = 30% Py	5	2.23	1.83

Table 2. Comparison of Nonlinear analysis with simplified method (n = 5), modified Pacoima Dam record, dead load = 30% P_y.

Model freq. (Hz)	μ	(1) Nonlinear analysis F_μ	μ'	μ_e	(2) Predicted F_μ	R = (2)/(1)
	1.73	1.33	2.04	1.21	1.26	0.950
	2.38	1.55	2.97	1.39	1.47	0.950
4	4.98	2.23	6.69	2.14	2.17	0.972
	5.92	2.51	8.03	2.41	2.39	0.950
	6.67	2.83	9.10	2.62	2.55	0.901
	1.97	1.34	2.39	1.28	1.34	1.003
	2.67	1.49	3.39	1.48	1.56	1.047
7	4.87	1.82	6.53	2.11	2.14	1.177
	5.72	1.94	7.74	2.35	2.34	1.206
	6.58	2.06	8.97	2.59	2.53	1.228
	1.29	1.26	1.41	1.08	1.11	0.880
	1.93	1.47	2.33	1.27	1.33	0.905
10	2.68	1.83	3.40	1.48	1.56	0.854
	4.68	2.29	6.26	2.05	2.10	0.915
	6.50	2.75	8.86	2.57	2.51	0.914
	1.70	1.28	2.00	1.20	1.19	0.932
	3.30	1.53	4.29	1.66	1.52	0.992
20	4.44	1.66	5.91	1.98	1.70	1.023
	5.67	1.79	7.67	2.33	1.87	1.043
	6.94	1.91	9.49	2.70	2.02	1.058

Table 2A. Comparison of nonlinear analysis with simplified method (n = 6), modified Pacoima Dam record, dead load = 60% P_y

Model freq. (Hz)	μ	(1) Nonlinear analysis F_μ	μ'	μ_e	(2) Predicted F_μ	R = (2)/(1)
	1.56	1.42	2.40	1.23	1.29	0.911
4	2.41	1.89	4.52	1.59	1.67	0.883
	3.62	2.36	7.55	2.09	2.13	0.902
	5.02	2.83	11.05	2.68	2.59	0.916
	1.83	1.40	3.08	1.35	1.42	1.015
7	2.88	1.69	5.70	1.78	1.86	1.099
	4.14	1.97	8.85	2.31	2.31	1.172
	5.57	2.25	12.43	2.91	2.76	1.227

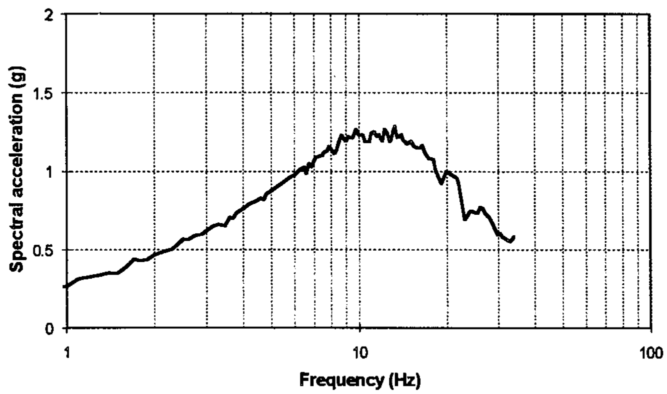


Figure 1
5% damped response spectrum of the
Modified Pacoima Dam Time History

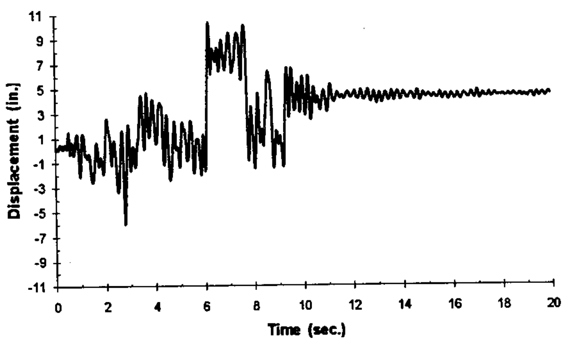


Figure 2
Response time history
for the case without dead load

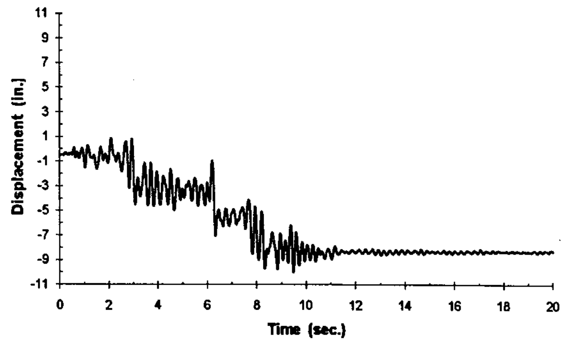
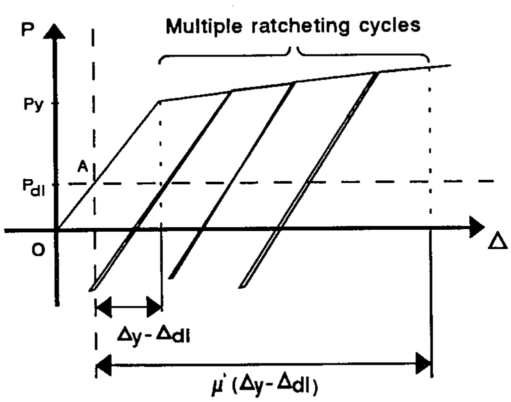


Figure 3
Response time history for the
case with dead load equal to
30% yield capacity



$$\text{Effective Ductility} = \frac{\left(\frac{\mu' - 1}{n}\right)\left(\Delta_y - \Delta_{dl}\right) + \left(\Delta_y - \Delta_{dl}\right)}{\left(\Delta_y - \Delta_{dl}\right)}$$

$$\mu_e = \frac{1}{n}\left(\mu' - 1\right) + 1$$

Figure 4
Effective ductility considering dead load and cyclic loading