EXPERIMENTAL DETERMINATION OF DAMPING IN REINFORCED CONCRETE FRAME STRUCTURES

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SUMMARY

This paper presents the results of free vibrations of a simple reinforced concrete structure, which is considered to behave as a single-degree-of-freedom one. Tests were performed for four different top masses and several initial displacements. At each experiment, the top velocity was recorded and the corresponding ratio of critical damping and natural period were calculated for each cycle. The results show that both the damping and the natural period increase with the amplitude of the vibration, while the past history of the excitation seems also to affect these parameters. It was also observed that the damping increases with the period.

DESCRIPTION OF THE TEST

The scepimen under test consisted of five pieces of reinforced concrete, assembled together at the Laboratories of the Public Works'Research Institute at Chiba/ Tokyo, Japan. Details on the dimensions and the reinforcement of the specimen are given in Figure 1. The base was anchored to the floor by several bolts to prevent rocking. The two frames comprising the columns were set at the front and back sides of the base and the contact surfaces were coated with a special concrete bond. The head beams were put in place using the same procedure. The pieces were fastened together through long screwed bars with a force of about 5 KN per steel bar. The columns were connected in the transverse direction with girders in order to avoid torsional vibrations as much as possible.

The experiments were performed for four different top masses, as it is shown in Figure 2. In step A, no mass was added at the top and only the dead weight of the structure was considered. In steps B and C, additional load blocks were added at the top. In step D, one of the load blocks of step C was removed and the load block 4 was put in such a position that the center of gravity of the top mass was at the middle of the top. The values of the top mass for the four loading steps (including half of the weight of the columns) and the corresponding theoretical natural periods of the structure are shown in table I. The value of the stiffness was calculated to be 1215.3 $KN\,m^{-1}$ assuming that both ends of the columns are clamped. The Young's modulus for the concrete was taken equal to 21 GPa.

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For each loading step, several experiments were performed for various initial displacements. The initial displacement was applied by pulling the top mass with a force Q_x and then suddenly release it. The values of Q_x, together with the maximum resulting moments and the theoretical initial displacement at the top, are shown in table II.

In table III, the applied maximum and minimum concrete stresses are shown for each experiment. It must be noted that the maximum stresses were, in all cases, lower that 2 MPa, which is assumed to be the strength of concrete in tension. In some cases, however, the maximum stresses are positive and, therefore, some small cracks in the concrete may start to form. We can assume,however that the behavior of the structure lies in the elastic regime.

The free vibrations of the structure were recorded by two velocity meters put at the edges of the top. The transverse motion of the mass was also measured to ensure that no torsional oscillations were occuring.

PRESENTATION OF THE RESULTS

In Figure 3, the calculated ratio of critical damping is plotted versous the normalized amplitude of vibration $A\omega^2/g$, for load steps A and D. Similar plots have been drawn for the experiment sets B and C which are not presented here for brievity. The quantity $A\omega^2/g$ can be thought as the ratio of the amplitude, A, over the static deflection which would occur under a horizontal gravitational field. This quantity, is also equal to the ratio of the amplitude of the acceleration over the acceleration of gravity.

The ratio of critical damping was calculated using the method of the logarithmic decreament of the amplitude for each cycle. The amplitude of the vibration was found by dividing the velocity amplitude by the corresponding frequency of the cycle. In order to avoid numerical errors resulting from the reading of the records as much as possible, the average of two consecutive amplitudes (at $t=t_n$ and $t=t_n+\frac{T}{2}$) was considered. The final value of the amplitude for each cycle was found by taking the mean value of the two records in the direction of motion. It should be noted that for some experiments a few first cycles of vibration were not recorded clearly because of some instrumental instability and as a result the information on the initial amplitudes is limited.

The large variation of damping for consecutive cycles, which is shown in some cases in Figure 3, is mainly due to the direct evaluation of the results from the raw data without any filtering and smoothing. It should be noted that these plots would be much smoother if the damping were calculated by considering the ratio of the initial amplitude over the amplitude of n^{th} cycle. i.e.:

$$\zeta = \frac{1}{2\pi n} \ell n \frac{A_o}{A_n} \tag{1}$$

instead of

$$\zeta = \frac{1}{2\pi} \ell n \frac{A_n}{A_{n+1}} \tag{2}$$

which was used in the present communication. In spite of this big scattering of the results, however, it can be concluded that the damping generally increases with the amplitude of the vibration as it is shown from the regression lines plotted on the same figure . The phenomenon mainly happens due to the formation of microcracks and probable local plastic areas, due to material inhomogeneity, both absorbing energy. It is interesting to note that some of the microcracks do not seem to close as the amplitude of vibration drops down, since the damping for a certain value of $A\omega^2/g$ and the same top mass is generally bigger for larger initial displacement.

The dependence of the damping on the previous loading history is also shown by comparing the plots of Figure 3. Because of the repeated loading of the structure during the test sets A, B and C, which were performed previously than the step D, the values of the damping for the set of the experiments D are much higher that those for step A.

It is also interesting to note that for the load step D, the increase of damping with amplitude is not so much pronounced as it is for load step A (Figure 3). This happens because most of the energy dissipation causing mechanisms are already formed during the previous loading history and thus, for step D and for the amplitudes considered, only a few more are created as the amplitude increases.

In general, it can be said that for the structure under test the value of the ratio of critical damping varies from about 2% to about 4%. It should be reminded here that all these tests were performed in the linear regime. The damping is expected to increase significantly for higher amplitudes which would cause yielding. It should be pointed out that a part of the energy is transmitted through the foundation to the ground.

The variation of the natural period with amplitude is shown in Figure 4 for load steps A and D. In these drawings the ratio of the period of vibration, T, of each cycle over the theoretically calculated natural period, To, (see table I) is plotted versus the normalized amplitude $A\omega^2/g$. Although there is a significant scattering of the results, a trend of the period to increase with amplitude is evident as it is shown from the regression lines. Most probably , this is due to an increased stiffness degradation with amplitude because of the microcracks which are generated. As it was mentioned above, some of these microcracks remain after the amplitude decreases and this is the reason why, similarly to the damping, the period depends, too, on the maximum amplitude experienced. Also, the loading and unloading history seems to be important. Thus, the average period for laod step D is significantly higher than the corresponding theoretical value, while for the load step A the mean value of the period is close to the theoretical one. This phenomenon can be explained by assuming that the loading of the structure during the tests A,B and C caused a permanent degradation of the stiffness.

In Figure 5 a representative plot of the variation of the damping with the frequency of oscillation ω, for tests A and D are presented. From the regression lines of this figure it is shown that the damping decreases as the frequency increases.

Finaly, in Figure 6 the ratio of the energy dissipated per cycle devided by the energy at the beginning of the cycle is plotted for each cycle for the tests A and D. The energy is measured by the value of the kinetic energy at the time when the velocity attains a local maximum, assuming that the displacement is zero at the point, i.e.:

$$\left(\frac{\Delta E}{E}\right)_n = \frac{\dot{u}_n^2 - \dot{u}_{n+1}^2}{\dot{u}_n^2} \tag{3}$$

The results of tests B and C which are not presented here show similar trends.

CONCLUSIONS

The results of the experiments performed show that the natural period and the ratio of critical damping of the simple concrete structure seem to depend significantly on the amplitude of the vibration, even in the elastic regime. These parameters increase as the amplitude increases and seem to be affected by previously experienced large amplitudes of vibration. Especially for the damping, the variation between maximum and minimum values found is very big. As a result, it is evident that the modeling of the structure as a single-degree-of-freedom system with constant eigenperiod and ratio of critical damping may be inaccurate.

ACKNOWLEDGEMENTS

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TABLE I

Masses and Corresponding Initial Natural Periods

STEP:	1	2	3	4
m(t)	2.35	6.22	10.51	14.78
To(sec)	0.28	0.45	0.58	0.69

TABLE II

Pulling force (Qx), resultant moment (Mx) and the theoretical initial response, for the various experiments

No of Experiment:	1	2	3	4	5	6
Q_x(KN)	0.50	1.00	1.50	2.00	2.50	3.00
M_x(KN cm)	1625	3250	4875	6500	8125	9750
Δ (cm)	0.0352	0.0705	0.1057	0.1410	0.1762	0.2115

TABLE III

Maximum and Minimum Concrete Stresses (in MPa)

	Pulling Force Q_x(KN)	Load Step A		Load Step B		Load Step C		Load Step D	
		σ_{max}	σ_{min}	σ_{max}	σ_{min}	σ_{max}	σ_{min}	σ_{max}	σ_{min}
1	0.5	0.076	-0.825	-0.460	-1.363	-1.054	-1.957	-1.649	-2.552
2	1.0	0.529	-1.277	-0.001	-1.814	-0.603	-2.409	-1.197	-3.003
3	1.5	0.980	-1.728	0.443	-2.265	-0.152	-2.860	-0.746	-3.454
4	2.0	1.432	-2.179	0.894	-2.717	0.300	-3.311	-0.295	-3.906
5	2.5					0.751	-3.763	0.157	-4.357
6	3.0					1.203	-4.214	0.608	-4.809

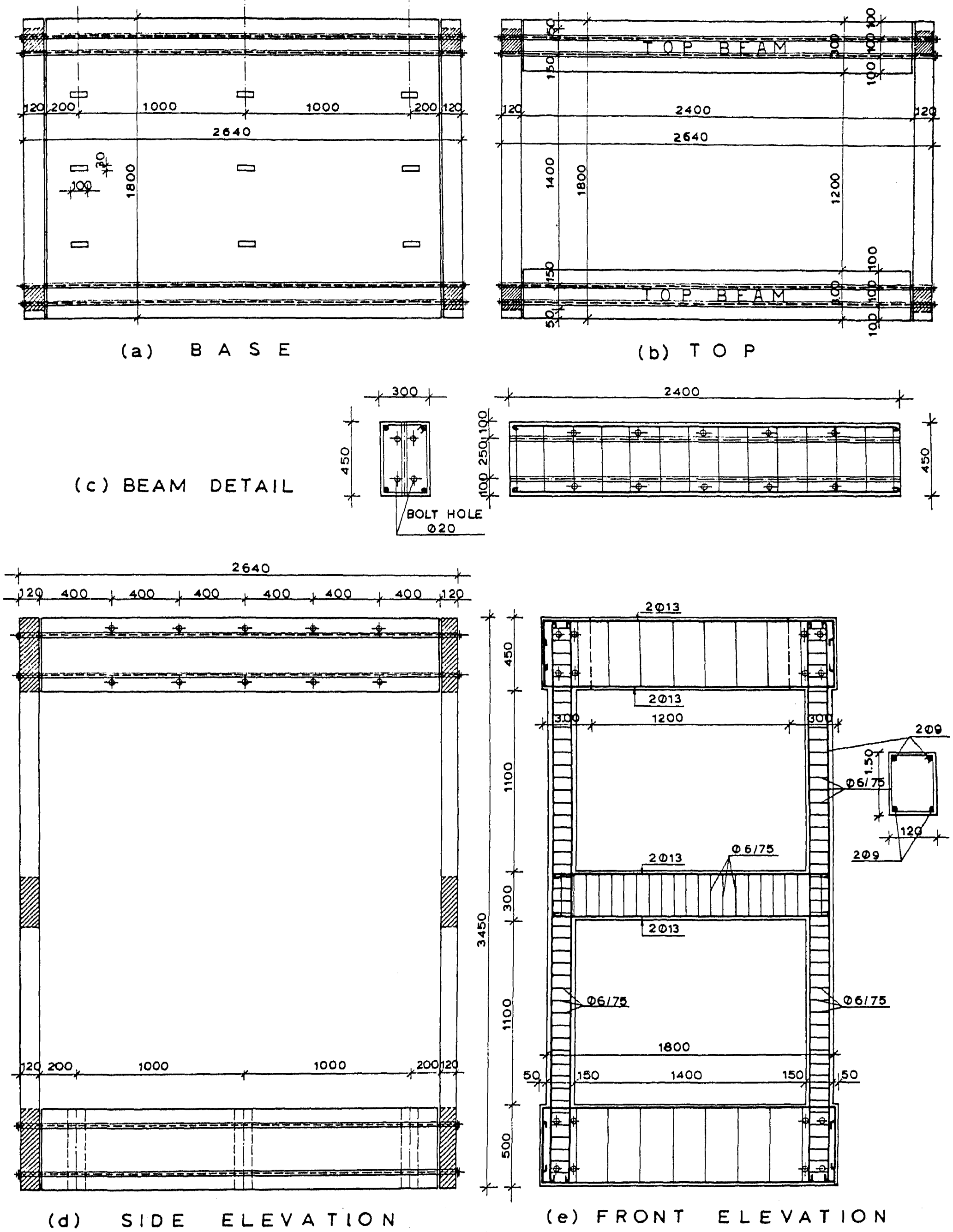

Fig.1 Details on the construction of the structure under test.

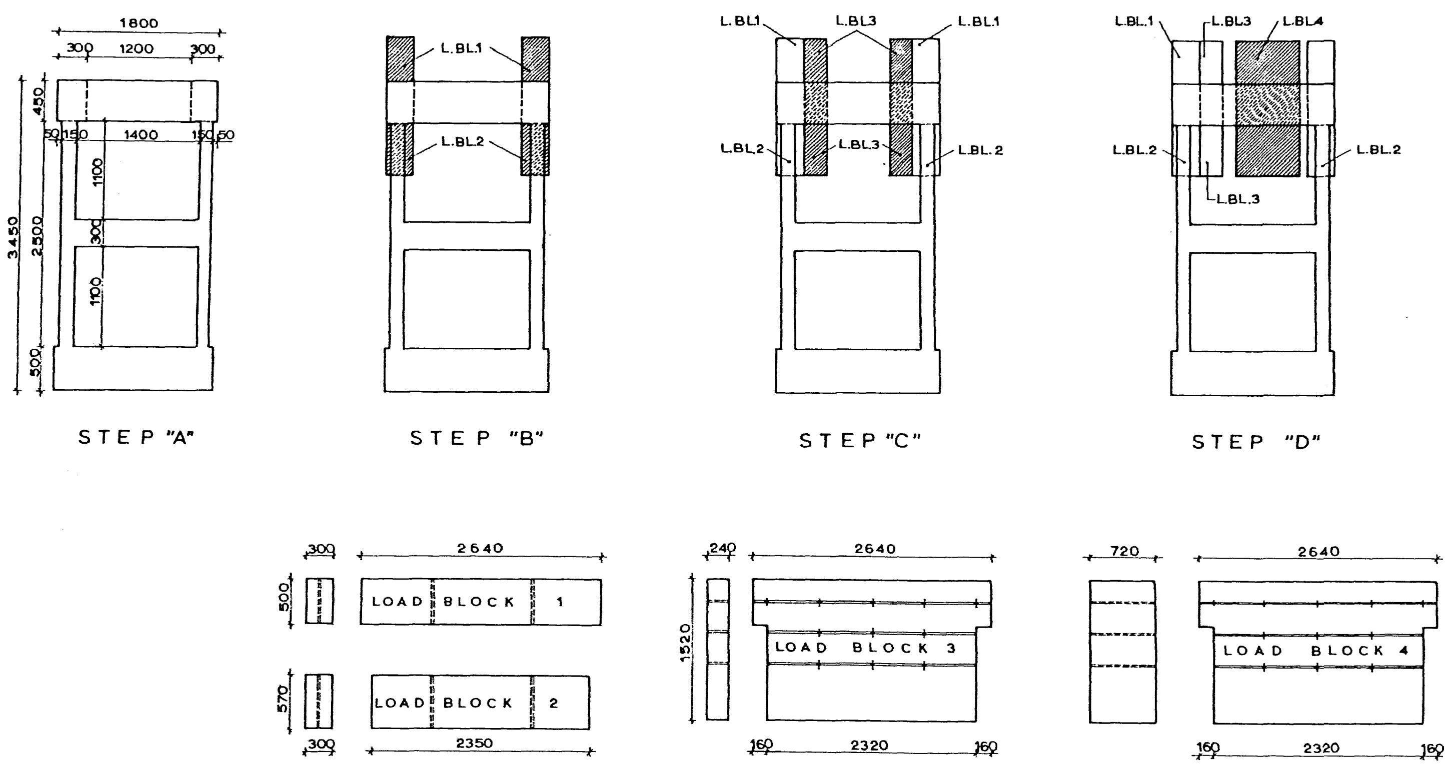

Fig.2 Setting of the top weights for the various load steps.

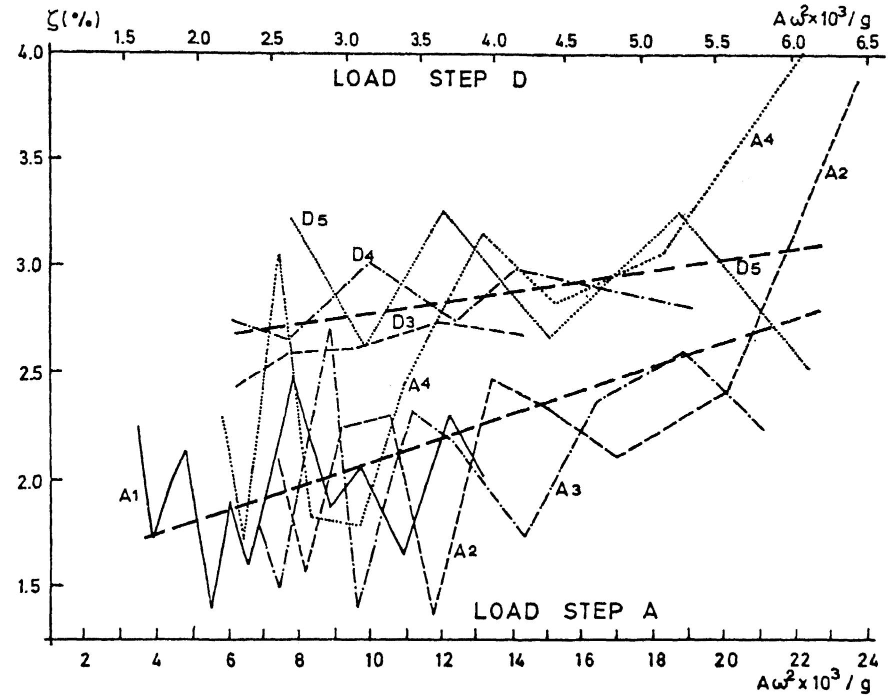

Fig.3 Dependence of the ratio of critical damping on the normalized amplitude of oscillation for load steps A and D.

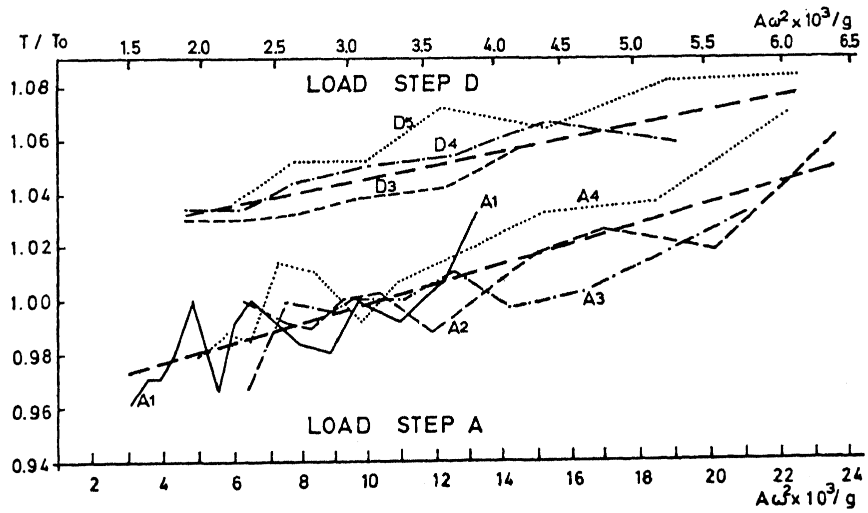

Fig.4 Dependence of the period of vibration on the normalized amplitude for load steps A and D.

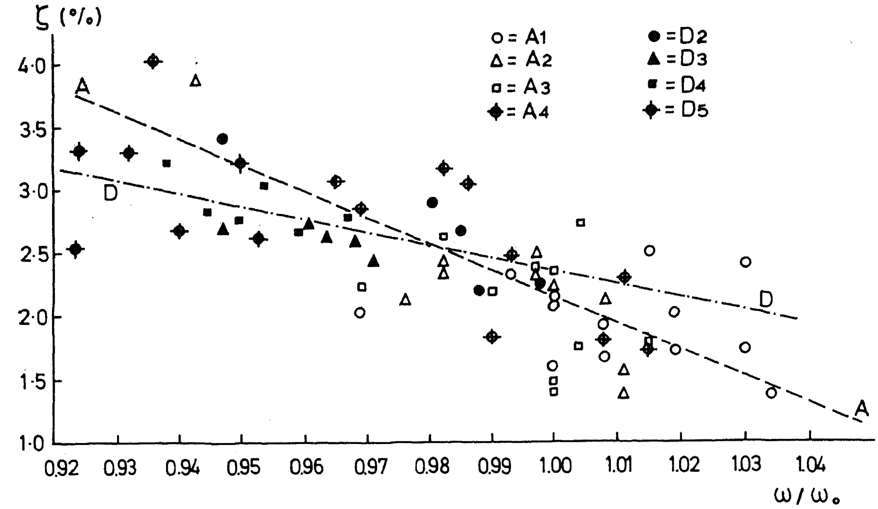

Fig.5 Variation of the ratio of critical damping with the frequency of oscillation for load steps A and D.

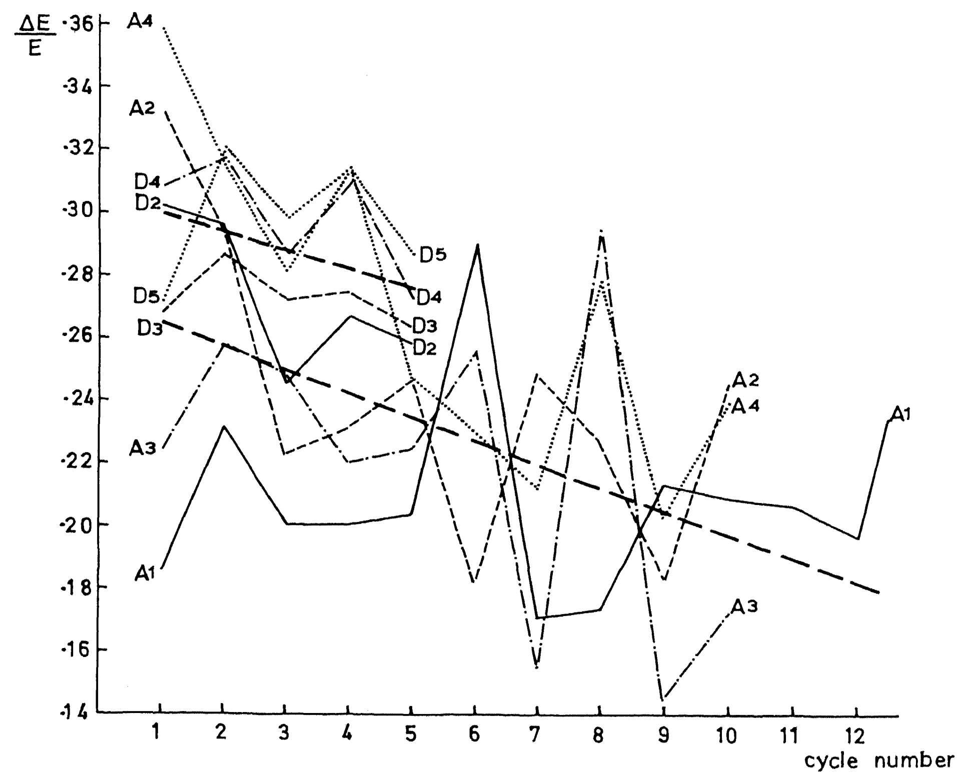

Fig.6 Normalized energy dissipation per cycle for load steps A and D.