THE EXPERIMENTAL STUDY ON THE DYNAMIC BEHAVIOR OF REINFORCED CONCRETE FRAMES

by Toshio Shiga* and Junji Ogawa**

INTRODUCTION The availability of large electronic computers has made it possible to analyze the response of buildings through various assumptions. But we cannot recognize exactly the true response of actual buildings without knowing dynamic behavior of structures. So we study the dynamic properties of buildings in the field extended into plastic range.

This paper presents the test results on the reinforced concrete frames subjected to the static and dynamic loading. The dynamic load was applied to the test specimens with a large-scale vibrating table system. And these are arranged with respect to the equivalent viscous damping, the equivalent rigidity and the dynamic hysteresis loop.

TEST SPECIMEN The test specimens were made of reinforced concrete, and designed to represent a single-story, one-bay, rectangular portal frame with fixed-based columns. It had a nominal span of 130 cm and a height of 160 cm. Heavy weights made of lead were attached to the girder level in order to reduce the natural frequency of the test specimen, till it was suitable for dynamic loading, and could be regarded as a single-degree-of-freedom system for the analysis.

TESTING PROCEDURE The testing methods were dividied into three. Method I was designed to compare the dynamic load-deflection curves with the static ones under the same loading condition. Method II was designed to yield the decrease of the frame rigidity during the static test. Method III was designed to yield the frame rigidity, the damping capacity and the dynamic hysteresis loop in a pure dynamic loading test.

TEST RESULTS Fig. 3 shows a typical static hysteresis loop. Dynamic hysteresis loops were obtained successfully. A representative dynamic loop is shown in Fig. 4, which obtained as a Lissajous patern by plotting the deflections and the accelerations measured at the very same time from the records of the oscillograph.

The rigidity decreased with an increase of deflection as shown in Fig. 5. The dynamic equivalent frame rigidity showed the same behavior as the static one. When several tens of repeated dynamic loads were applied to vibrate the specimen in certain amplitudes, the frame rigidity decreased a little. The dependency of the frame rigidity on the deflection follows a hyperbolic function. It became one-fourth of the initial value at a column translation angle of 0.005, and one-ninth at 0.025.

The equivalent viscous damping factor was calculated with the application of the method suggested by Lydik S. Jacobsen and is plotted in Fig. 6 against the deflection. The damping factor increased almost rectilinearly with the increment of the deflection. The value of the damping factor became 0.13 at the column translation angle of 0.04, and, thereafter, it had a tendency to decrease slightly.

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SYNOPSIS

This investigation reports on the determination of the dynamic properties of reinforced concrete bents through experiments. The test specimens were single-story, one-bay portal frames which were subjected to sinusoidal motions of a large-scale vibrating table in dynamic tests. The results of the dynamic test were discussed with respect to the equivalent frame rigidity and to the equivalent viscous damping factor, and were compared to those of static tests. The dynamic hysteresis loops were successfully obtained. Compared at the same amplitude, these were similar to the static ones, and were found to belong to a hardening spring type. The reduction of the rigidity, obtained from the dynamic test, corresponded to that in the static case. The damping capacity had a tendency to increase with the amplitude. It's maximum value was 0.13 at a column translation angle of 0.04.

INTRODUCTION

The general problems associated with the design of structures to withstand externally generated oscillations have been of great interest to the engineers in various fields. The response problem of a building structure subjected to earthquake motions is a special problem of the general structural dynamics. The character of an earthquake excitation differs from that of general excitation as e.g., in machines or airplanes. The actual building structure might be vibrated in high stress during strong earthquake motions, but the number of cycles might be only between ten and twenty.

In recent years, the availability of large electronic computers made it possible to compute these oscillation response in both the elastic and the inelastic range, and various response analyses have been performed. Due to the lack of sufficient data on the dynamic properties of building structures which formed the foundation of these response analyses, the results have to be considered with reservation. In order to make response analyses more meaningful, it is necessary to know the dynamic properties of building structures, such as the damping capacity and the hysteresis properties, especially in the inelastic range.

LABORATORY PROGRAM

MATERIALS The concrete which was designed for a 4-week strength of 180 kg/cm^2 was manufactured from normal Portland cement and natural aggregate. The maximum size of the gravel was 10mm. Pozzolith No. 5 was used as a dispersing agent (25 % solution : 5.6 ml/m^3). The proportion was 1.0 : 3.0 : 3.2 by weight. The cement strength was 410 kg/cm^2 in accordance with the Japan Industrial Standard's specifications. The water-cement ratio

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of the concrete, which was cast into R-type specimens, was 0.53 by weight, and the slump was 15 cm. The corresponding values of the concrete placed into R-A-type specimens were 0.61 and 18 cm. The average ultimate strength of the concrete was approximately 210 kg/cm^2, as determined by compression tests on 30 cm by 15 cm standard cylinder specimens according to the Japan Industrial Standard's specifications.

D10 deformed bars were used as principal reinforcement. 1-D10 had a cross section area of 0.71 cm^2. The bars were made of high strength steel with a yield point of 3,600 kg/cm^2, and an ultimate strength of 5,500 kg/cm^2 with 23.3 percent elongation as determined by standard laboratory tests.

TEST SPECIMEN The test specimens were designed to represent a single-story, one-bay, rectangular portal frame with fixed-based columns. It had a nominal span of 130 cm and a height of 160 cm. Figs. 1 and 3 illustrate the details of the model frame configuration, reinforcement distribution and stirrup spacing. Figs. 2 and 4 show photos of R-type and R-A-type specimens.

Reinforcement used in both the beam and the column were four D10 deformed bars. Two of these bars were used as tensile reinforcement, and the others served as compression reinforcement. The total reinforcement ratio of the column was 1.59 percent. The stirrup was a thick annealed wire of 4 mm diameter.

Heavy weights made of lead were attached to the girder level in order to reduce the natural frequency of the test specimen till it was suitable for dynamic loading, and could be regarded as a single-degree-of-freedom system for the analysis. Their weights were about 500 kg. The calculated natural frequency of the R-type was 9.7 cps ($k = 2.6$ t/cm) and that of the R-A-type was 9.3 cps ($k = 2.9$ t/cm). The ultimate strength of the test specimens was approximately 1.2 t for both types.

The test specimens were cured in a plywood form in normal air until the time of the test, which took place from six to 72 weeks after the specimens were cast. After removal from the form, the surfaces of the test specimen were covered with a very thin layer of plaster. This coating was applied to enhance the visibility of cracks during the loading tests.

INSTRUMENTATION AND LOADING APPARATUS The measuring equipments were designed to record the applied load, the deflections and the accelerations during this experimental program. The loading apparatuses were arranged in such a way that measurements could be performed up to a test specimen failure depending on the purpose of the test.

1) Static Test The load was applied with a chain block or an oil jack. The maximum capacity of the chain block was 1.5 t, and that of the oil jack was 10.0 t. The load which was applied with the chain block, was measured with a tension type dynamometer with a maximum capacity of 3.0 t. If the oil jack was used, a compression type dynamometer with a maximum capacity of 2.0 t was employed. Each dynamometer had a mechanical dial indicator, which had a maximum travel of 3.0 mm and was marked in subdivisions of 0.01 mm.

A mechanical dial indicator or a stainless steel scale were used to measure the deflections of the test specimens. They were placed on the mid-span of the portal frame at the girder level. It was not convenient to measure large deflections with the dial indicator, it was only applied for deflections of less than 100 mm. The dial indicator had a maximum travel of 50 mm and was marked in subdivisions of 0.01 mm. The steel scale was 1,000 mm in length and was marked in subdivisions of 1.0 mm. Readings of the loads and the deflections were taken at certain load intervals and noted as fast as possible. If the test specimen was subjected to a sustained load in the inelastic deflection range, it continued to deform or creep for an indefinite time after the first application of load. During the static loading tests, the displacements at the base of the test specimens were also measured with the dial indicator. These were very small, and therefore they could be neglected.

2) Dynamic Test The dynamic load was applied with a large-scale vibrating table system. The schematic diagram and the photo of this system are shown in Figs. 5 and 6. It is installed in the Structural Laboratory of the Architecture Department, Faculty of Engineering, Tohoku University. The mechanical vibrating exciter consists of a pair of counter-rotating eccentric counter-balanced baskets located on dual vertical shafts and driven in opposite directions by a gear system. It is possible to vary widely the sinusoidal horizontal inertia force output of the exciter by fitting additional weights into both baskets. The gear drive system of the exciter has a three step gear box and is driven by a 11 kw A.C. motor. The number of rotations of this motor can be varied from 450 rpm to 1,350 rpm. Therefore, the frequency range of the exciter's output is changeable from 4.63 cps to 0.39 cps. By means of the manual adjustment of the frequency of the exciter, this vibrating table system can excite the testing bents easily either in the resonance state or in the steady state at any frequency ratio.

As the vibrating table is supported by spring plates and equipped with oil dampers, it can be regarded as a damped single-degree-of-freedom system. The response property and acceleration of the table can be widely changed by means of the number of oil dampers fitted, the frequency of the output force of the exciter, and the weight of the eccentric mass in the baskets. Fig. 7 shows the relation of the acceleration response versus the period of the exciting force.

The measurement of the deflection and the force in a dynamic loading test is a very complex problem. The deflections and the accelerations were transformed into electrical signals by means of a system, which consisted of strain gage-type transducers and a dynamic strain meter. These electrical signals were simultaneously recorded on an ink writing oscillograph and a magnetic tape recorder.

The deflection of the test specimen at the girder level and that of the vibrating table were measured with a home-made cantilever-type deflection transducer. It consisted of electrical resistance strain gages, a flexible cantilever-type beam and a special sliding pivot supporter. The flexible beam was supported in the transverse direction of the deflection by a sliding pivot. The electrical resistance strain gages were mounted on the beam. The natural frequency of this system was approximately 450 cps and it had a very small amount of damping. Therefore, there was no phase-lag between the deflection input and the electrical output.

The dynamic load was measured via the acceleration of the test specimen at the girder level. The acceleration was measured with a strain gage-type transducer. Its principle was a single-mass-system with a large amount of damping (damping factor : 0.7), and a natural frequency of 200 cps. As the frequency of dynamic test program was much smaller, it was very small that the phase-lag between the input and the output depended on the amount of damping and the frequency ratio. Therefore, it could be neglected.

TESTING PROCEDURE The testing methods in this investigation were divided into three methods, i.e., Method I, Method II and Method III. Each method had the individual object.

1) Method I : This method was applied to R-2 and R-3 and was designed to compare the dynamic load-deflection curves with the static ones under the same loading condition. The main object of this method was that this comparison could be performed at almost the same amplitude of the specimen. Three loading steps with different deflections were employed : In the first step, the deflection was less than the yielding deflection of the principal reinforcement. In the second step, the deflection was slightly beyond the yielding deflection. In the third step, the deflection was twice the yielding deflection. Each loading step consisted of three loading tests. In each loading step, the specimen was subjected to the primary static cyclic loading test (S.T.P.), the dynamic loading test (D.T.) and the secondary static loading test (S.T.S.).

In the dynamic loading test, the test specimen was loaded up to the respective deflections by the vibrating table system. Watching the ink writing oscillograph, the amplitude of the vibrating test specimen was adjusted to the predetermined value by controlling the output of the exciter force and the frequency by hand, till the deflection in the dynamic loading test equal to that in the static one. Then, as a steady state cycling condition was reached, the test specimen was subjected to several tens of cycle-loadings to obtain the pertinent experimental results.

2) Method II : This method consisted of a static loading test on the specimens R-5 and R-A-1. The main object of this method was to obtain the decrease of the equivalent frame rigidity during the static test. The equivalent frame rigidity was calculated from the virgin load-deflection curve. Accordingly, the specimen was subjected to only one cycle-loading. An increasing static load was applied up to a deflection of ± 50 mm, which is equal to 1/30 radian of the column translation angle. This value was beyond the value of the yielding deflection.

3) Method III : This method was a dynamic loading test on specimens R-7, R-8, R-A-2 and R-A-3. The test was designed to yield the equivalent frame rigidity, the damping capacity and the dynamic hysteresis loop in a pure dynamic loading test. An increasing dynamic load was imposed on the virgin test specimen by means of the vibrating table system. In order to obtain the largest deflection in the test with the least number of repeated loadings, the frequency of the excitation was carefully controlled by hand. For, in order to stay near the resonant state, the frequency of the excitation had to be decreased to follow the reduction of the frame rigidity.

Figs. 10, 11, 12 and 13 show examples of the dynamic and the static hysteresis loops of the reinforced concrete specimens. The shapes of the loops show that the reinforced concrete structure is a damped nonlinear system. It is considered that the damping of the reinforced concrete structure is caused by many factors, i.e., structural damping, viscous damping, Coulomb damping, hysteretic damping, etc. Although the problem of the dynamic properties of the reinforced concrete structure is complex, we associated the behavior of the reinforced concrete specimens with a viscously damped linear structure. The dynamic properties of the damped linear structure were expressed in terms of the equivalent frame rigidity and the equivalent viscous damping factor.

When a single-degree-of-freedom viscously damped linear system is excited with a sinusoidal oscillation, its steady-state response is governed by the differential equation of the following type :

$$\ddot{x} + 2hn\dot{x} + n^2x = -x_op^2 \sin pt \quad \text{....................} (1)$$

Where x = the deflection of the frame; x_o = the amplitude of the excitation; n = the natural frequency; p = the frequency of the excitation.

There are two methods to obtain the dynamic hysteresis loops from the records made during the dynamic loading tests. In one case the loop was obtained as a Lissajous pattern by plotting the deflections and the accelerations measured at the very same time from the records of the oscillograph. In the second case the loop was generated as a Lissajous pattern with a X-Y recorder, which was driven by the signals from the magnetic tape recorder.

DAMPING AND RIGIDITY FROM DYNAMIC HYSTERESIS LOOPS The shapes of the dynamic hysteresis loops, obtained from the loading tests of the reinforced concrete structure, were not equal to those derived from the viscously damped linear system, but the equivalent viscous damping factor (h_{eq}) could be calculated by an extension of the method proposed by L.S. Jacobsen. It is impossible to determine the true rigidity of the vibrating structure in the inelastic range. In this paper, the equivalent frame rigidity (K_{eq}) was defined as the slope of the line going through the ends of the hysteresis loops. The calculation of h_{eq} and the measurement of K_{eq} from the hysteresis loop (called "Geometrical Energy Method" by Paul C. Jennings(1)) are illustrated in Fig. 13. It follows that :

$$h_{eq} = \frac{\varphi}{2\pi}\frac{ACB}{OCD} \qquad \left(\varphi = \frac{n}{p} \right)$$

$$K_{eq} = \frac{CD}{OD}$$

DAMPING AND RIGIDITY FROM DYNAMIC MAGNIFICATION FACTOR AND PHASE-LAG

The equivalent viscous damping factor ($h_{e\theta}$) and the equivalent frame rigidity ($K_{e\theta}$) can be obtained from the dynamic magnification factor and the phase-lag, by means of the equations of viscously damped linear system under a sinusoidal excitation. They are given as :

$$h_{e\theta} = \frac{\sin\theta}{2e\sqrt{1 + \frac{\cos\theta}{e}}}$$

$$K_{e\theta} = p^2 m \left(1 + \frac{\cos\theta}{e} \right) \qquad (e = x_{max}/x_o)$$

Where θ = the phase-lag between the table motion and the deflection; e = the dynamic magnification factor; m = the mass; p = the frequency of the excitation.

RESULTS AND INTERPRETATIONS

DYNAMIC HYSTERESIS LOOP The dynamic hysteresis loops were successfully obtained in the large deflection range. Fig. 13 shows a typical dynamic hysteresis loop of R-A-3 at a deflection of 65.5 mm (R = 0.041) measured by Method III. The dynamic hysteresis loop obtained with the X-Y recorder is shown in Fig. 11. Its shape is almost same as that of the loop plotted from the oscillographic data.

COMPARISON BETWEEN STATIC AND DYNAMIC HYSTERESIS LOOPS IN METHOD I

Figs. 10 and 11 show a comparison between the static hysteresis loops and the dynamic curves of R-2 and R-3 at the same deflection obtained by Method I. At the large deflections, the shape of the dynamic hysteresis loop is almost the same as that of the static one. The values of the equivalent frame rigidity are almost the same.

RIGIDITY The initial rigidity of the test specimens was obtained by a free vibration test. The initial rigidity of R-A-type was 2.8 t/cm and agreed with the value calculated from the elastic method (2.9 t/cm).

The static equivalent frame rigidity was determined from the static virgin load-deflection curve as shown in Fig. 12, and it is plotted in Fig. 14. The dynamic equivalent rigidity also plotted in Fig. 14, was calculated from the slope of the line going through the ends of the dynamic hysteresis loop.

The rigidity decreased with an increase of deflection as shown in Fig. 14. The dynamic equivalent frame rigidity showed the same behavior as the static one. When several tens of repeated dynamic loads were applied to vibrate the specimen in certain amplitudes, the frame rigidity decreased a little. The dependency of the equivalent frame rigidity on the deflection follows a hyperbolic function. The value of the frame rigidity dropped to one-half of the initial value within the range of small deflections. It became one-fourth atta column translation angle of 0.005, and one-ninth at 0.025. Thereafter, the equivalent frame rigidity decreased more slowly.

Fig. 16 shows the relation between K_{eq} and $K_{e\theta}$ calculated from the same record of the dynamic loading test. As shown in Fig. 16 the dynamic equivalent frame rigidities, calculated by the two different methods, were almost the same, indicating that either method can be employed to calculate the equivalent frame rigidities from the records of the dynamic loading test.

DAMPING FACTOR The equivalent viscous damping factor was calculated by the "Geometrical Energy Method" and is plotted in Fig. 15 against the deflection. The equivalent viscous damping factor increased almost rectilinearly with the increment of the deflection. The value of the damping factor became 0.13 at the column translation angle of 0.04, and, thereafter, it had a tendency to decrease slightly. The damping factor of the R-type was a little larger than the cracks on the panel zones. Fig. 17 shows the relation between h_{eq} and $h_{e\theta}$ calculated from the same record. The results are fairly scattered, which is considered to be caused by a strong effect of errors in the measurement of the phase-lag.

CONCLUSIONS

It is complex problem to investigate the dynamic properties of reinforced concrete structures. The fact, that the reinforced concrete is a non-homogeneous material, causes a wide scattering of the experimental data. However, according to the experimental results obtained in this investigation, the following general conclusions can be drawn.

1) The dynamic hysteresis loop is similar to the static hysteresis loop, when the amplitude in the dynamic loading corresponds to that of the static. The hysteresis loop belongs to a hardening spring type.

2) The reduction of the dynamic equivalent frame rigidity corresponds to that of the static case. When several tens of repeated dynamic loads were applied to vibrate the specimen in certain amplitudes, the frame rigidity reduced fairly.

3) The equivalent frame rigidity decreased with increasing deflections in a hyperbolic way. The value of the frame rigidity dropped to one-half of the initial value within the range of small deflections.

4) The equivalent viscous damping factor increased almost rectilinearly with the increment of the deflection. The value of the damping factor became 0.13 at the column translation angle of 0.04, and, thereafter decreased slightly.

There are numerous problems of the dynamic properties of reinforced concrete structures which are not discussed in this paper. Further studies are needed on these points.

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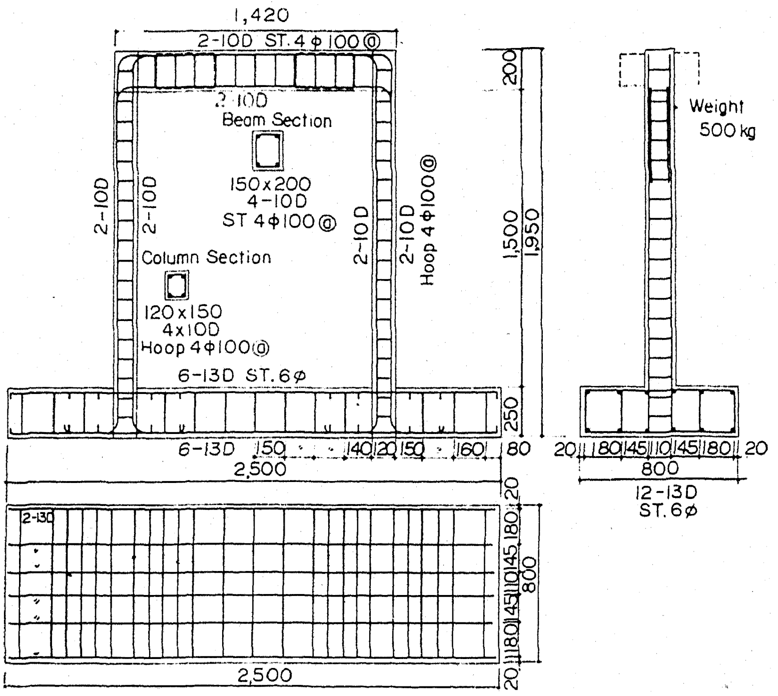


FIG. 1 THE SCHEMA OF A TEST SPECIMEN

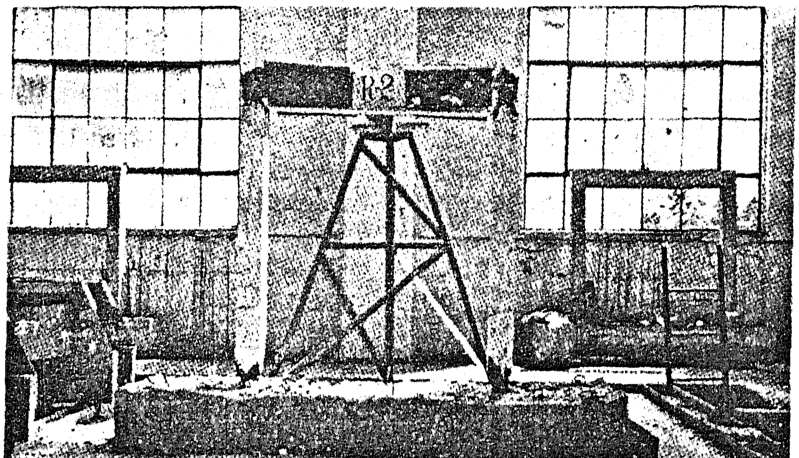


FIG. 2 THE PHOTO OF A TEST SPECIMEN

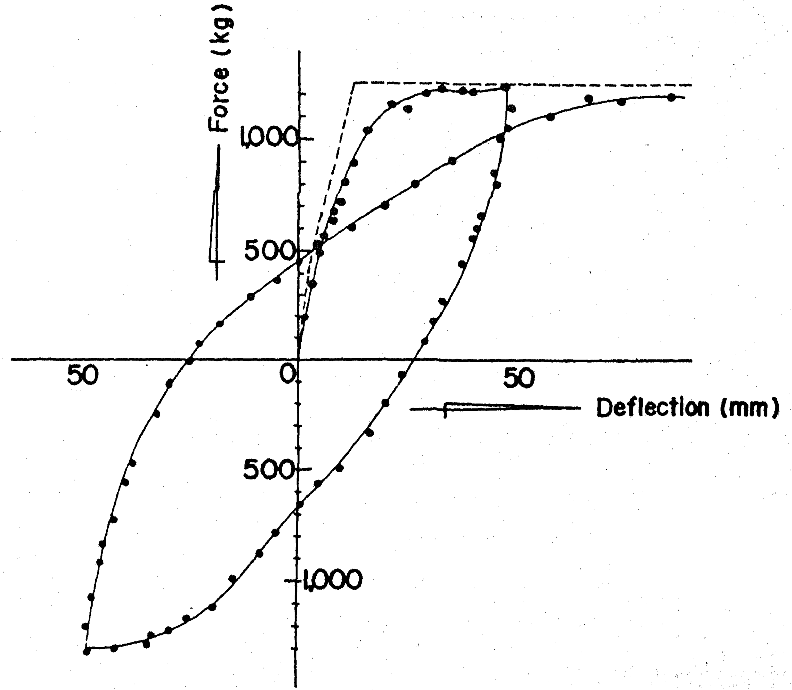
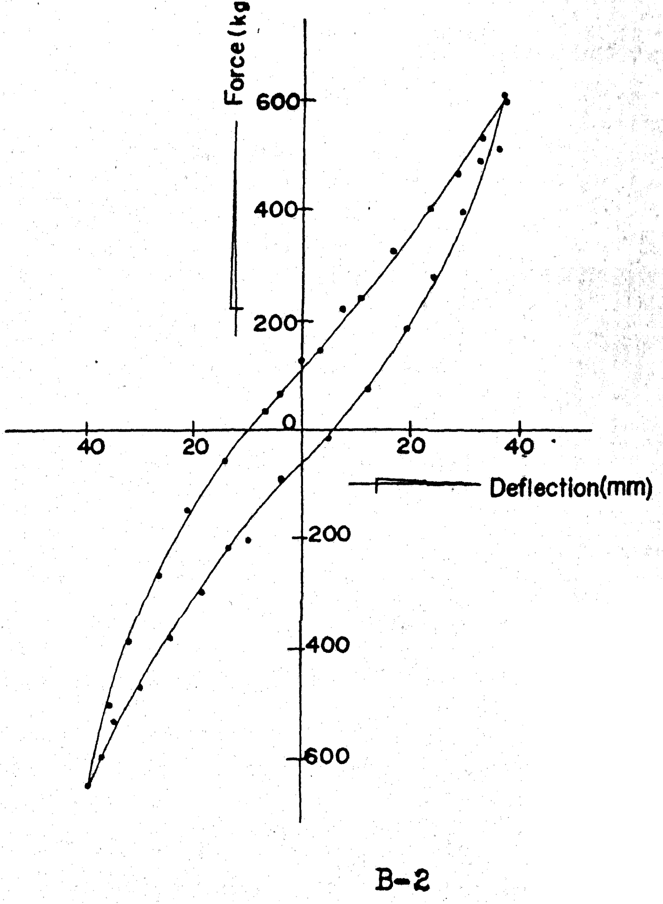

Force (kg)
1,000
500
50
0
50
Deflection (mm)
500
1,000

FIG. 3


Force (kg)
600
400
200
0
40
20
20
40
Deflection(mm)
200
400
600

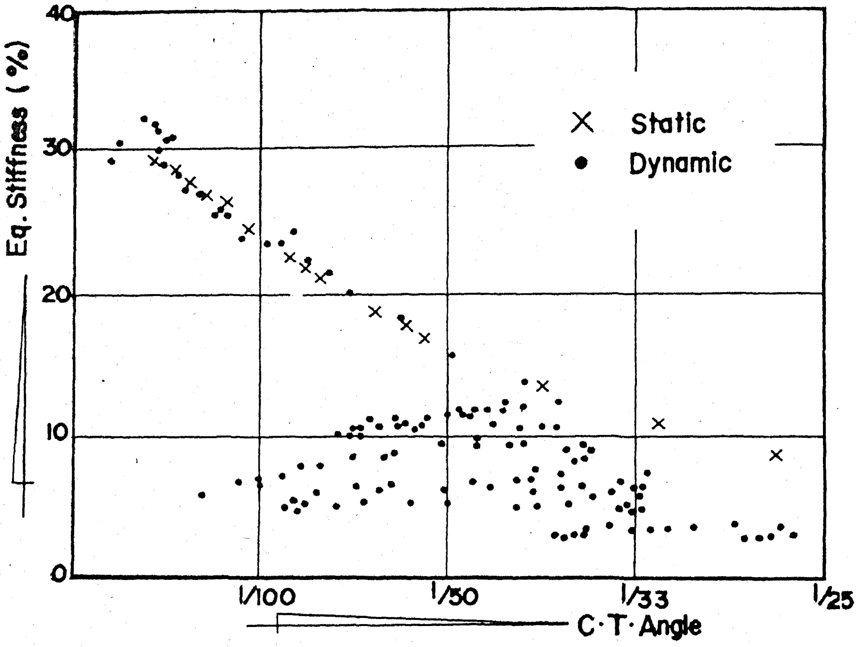

Eq. Stiffness (%)
40
30
20
10
0
Static
Dynamic
1/100
1/50
1/33
1/25
C·T·Angle

FIG. 5

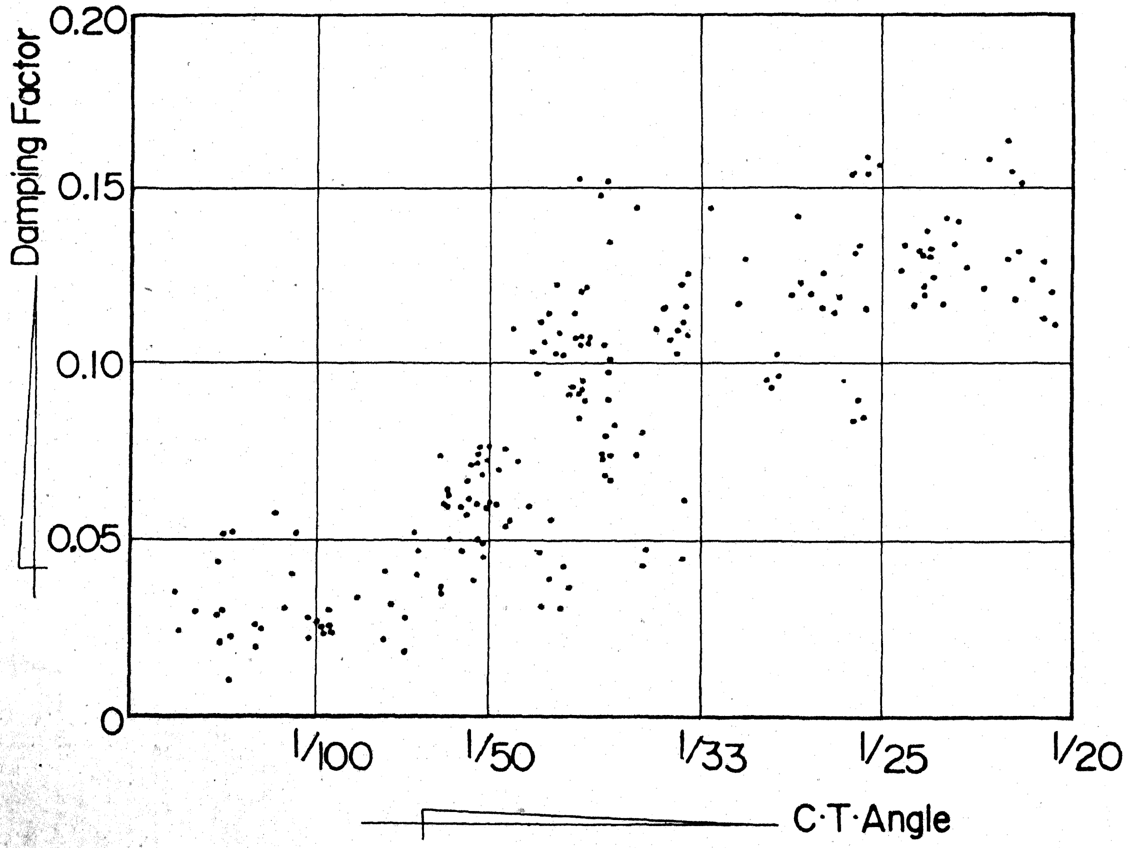

Damping Factor
0.20
0.15
0.10
0.05
0
1/100
1/50
1/33
1/25
1/20
C·T·Angle

FIG. 6