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ASD-TDR-62-717

Results of Loss Factor Measurements on Steel and Concrete Beams using a Viscoelastic or Sand Damping System

Nelson D. Wolf

288 079

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-717
September 1962

Deputy for Test and Support
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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Project 4437

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Aeronautical Systems Division, Dir/Engineering Test, Environmental Division, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-62-717. RESULTS OF LOSS FACTOR MEASUREMENTS ON STEEL AND CONCRETE BEAMS USING A VISCOELASTIC OR SAND DAMPING SYSTEM. Final report, Sep 62, 51 pp. incl illus. tables, & 15 refs.

Unclassified Report

The report contains the results of tests to measure loss factors on steel and concrete beams using a viscoelastic or sand damping system. The significance of the tests using the viscoelastic material was the rather large size of the system; for

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2. Structural Damping
3. Mechanical Damping
4. Vibration Mechanisms

I. AFSC Proj 4437
II. Wolf, Nelson D.
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FOREWORD

This report was prepared by the Sonic Branch, Structural Division, Directorate of Engineering Test, Deputy for Test and Support, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The work was conducted under Project No. 4437, "High Intensity Sound Environment Simulation." The tests and experimental work reported were conducted to support the design of the damping system for the large scale test chamber of the ASD Sonic Fatigue Facility. The author and project engineer, Nelson D. Wolf, was assisted in this work by Frank W. Mokry, III, who conducted a great part of the experimental and data reduction work. A portion of the work reported was obtained under Contract AF 61(052)-446 for which Dr. Gunther Kurtze was principal investigator.

ABSTRACT

This report contains the results of tests to measure loss factors on steel and concrete beams using a viscoelastic or sand damping system. The significance of the tests using the viscoelastic material was the rather large size of the system; for the sand damping system, data was obtained at frequencies down to 36 cps. Numerous configurations are tested. For the sand damping case, loss factors are measured as a function of acceleration.

This technical documentary report has been reviewed and is approved for publication.

George A. Kirsch

GEORGE A. KIRSCH
Colonel, USAF
Asst Deputy for Test and Support

REVIEW AND COORDINATION OF ASD TECHNICAL DOCUMENTARY REPORT 62-717

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

LIST OF SYMBOLS

δ	Logarithmic decrement
n	Number of cycles
x	Variable beam length
η	Loss factor
Δf	Bandwidth
f	Frequency
D_o	Total damping energy
W_o	Strain energy
X	Displacement amplitude
φ	Phase angle between force and motion
ω	Angular frequency
L	Length
E	Young's modulus
I	Moment of inertia
P	Force
y	Force displacement
C	Constant to be determined
m	Total mass
A	Area
H_2	Thickness (See figure 3.)

SECTION I

INTRODUCTION

The information and data found in this report have been an outgrowth of a combined in-house and contractor effort to study a damping system requirement to control the resonant vibrations of the main test chamber of the ASD Sonic Fatigue Facility. The structure of the main test chamber is composed of a steel framework with large concrete panels clamped in place on the steel girders and columns. The girders and columns have pinned end connections (figure 1). The main chamber will be used as a reverberation chamber and also as an anechoic chamber with sound-absorbing material covering the walls and ceiling. When the chamber is used in the reverberation mode the steel structure and walls will be subjected to sound pressure levels up to 160 db ref .0002 dynes/cm^2 and frequencies from 50 to 10,000 cps. This acoustic energy will be generated by sirens. Because of the wide range of frequencies involved it is impossible through design to eliminate structural resonances from the chamber. Therefore, a structure having girders, columns, and reinforced-steel concrete panels of considerable size must have a suitable damping system built into it.

The damping system under consideration consists of the following: Steel girders and columns of the underlying structure are damped by the use of viscoelastic material. One side of the viscoelastic material is bonded to the girder or column and the other side to a restraining layer sometimes called a damping beam. In the Sonic Facility this is simply another beam. Actual installation of the viscoelastic material consists of bonding it to two steel plates, which are, in turn, bolted to the girder and damping beam (figure 1). By attaching the material to the beams in this manner the shear damping properties of the material are utilized. The amount of damping can be calculated according to the well-developed theory given in section 3 of reference 1.

Damping of the concrete ceiling and wall panels, and concrete floor of the ASD facility is accomplished in a different manner. Steel boxes filled with a granular substance, best described as a "pea" gravel, are cast directly into the concrete (figure 2). The percentage by weight of the gravel to the reinforced concrete is twenty percent or better. The actual damping mechanism is described in sources listed in the bibliography. In essence, damping is obtained by the friction between adjacent granules as well as by the out-of-phase movement between the granular mass and the mass to be damped. To formulate a theory leading to calculation of the amount of damping in effect is troublesome because of the difficulty in obtaining a suitable mathematical model of the damping mechanism.

The criteria used in designing the damping system for the ceiling, wall panels, and floor of the main test chamber was taken from a study under Air Force Contract 61(052)-446 (ref 2). Also, design information such as box size, grain size, box placement, and ratio of granular substance to concrete was taken from this study.

Because of the difficulty in theoretically determining the magnitude of the damping, an experimental approach to determine the order of magnitude of the loss factors for the

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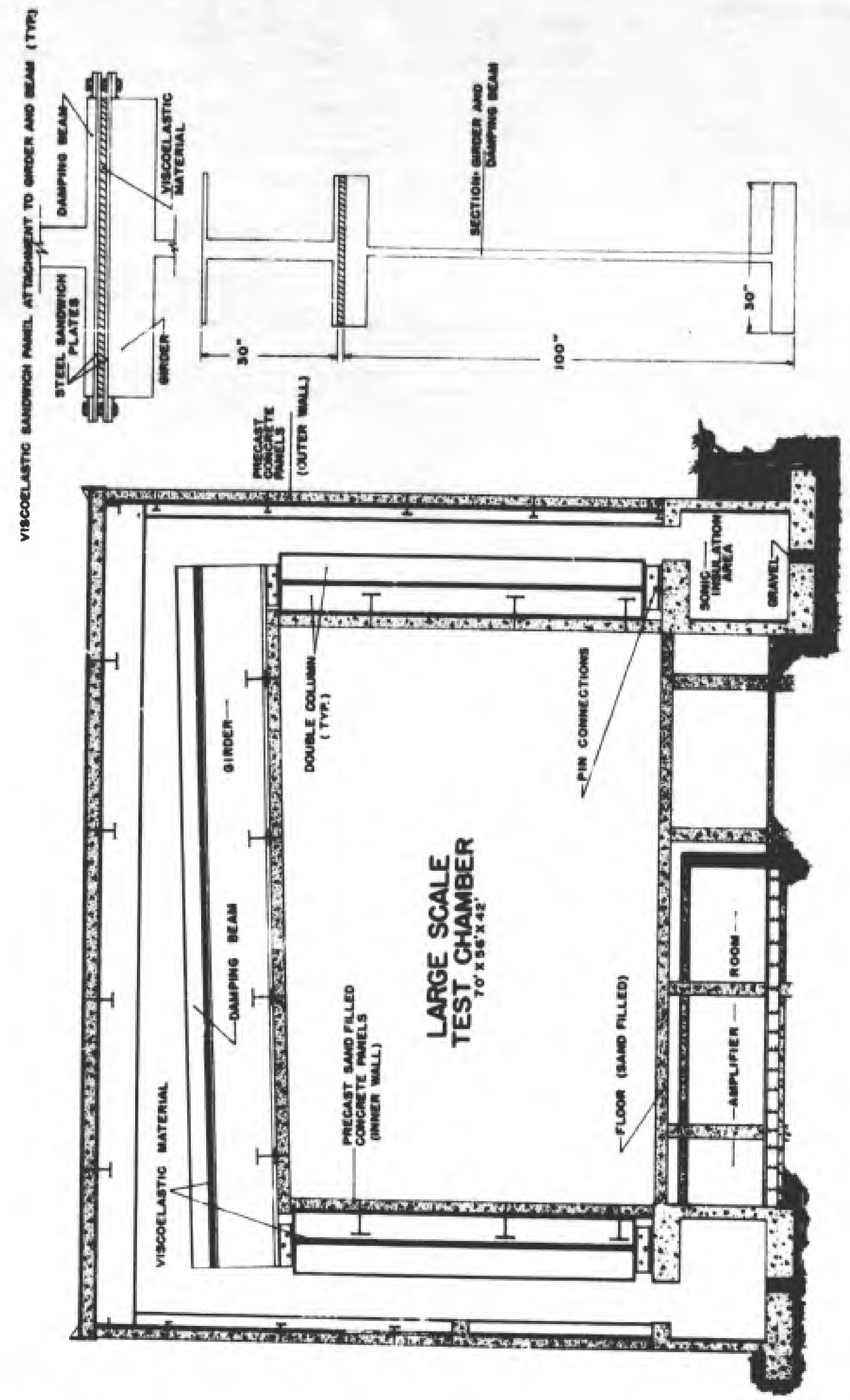


Figure 1. Sonic Fatigue Facility; Large Test Chamber

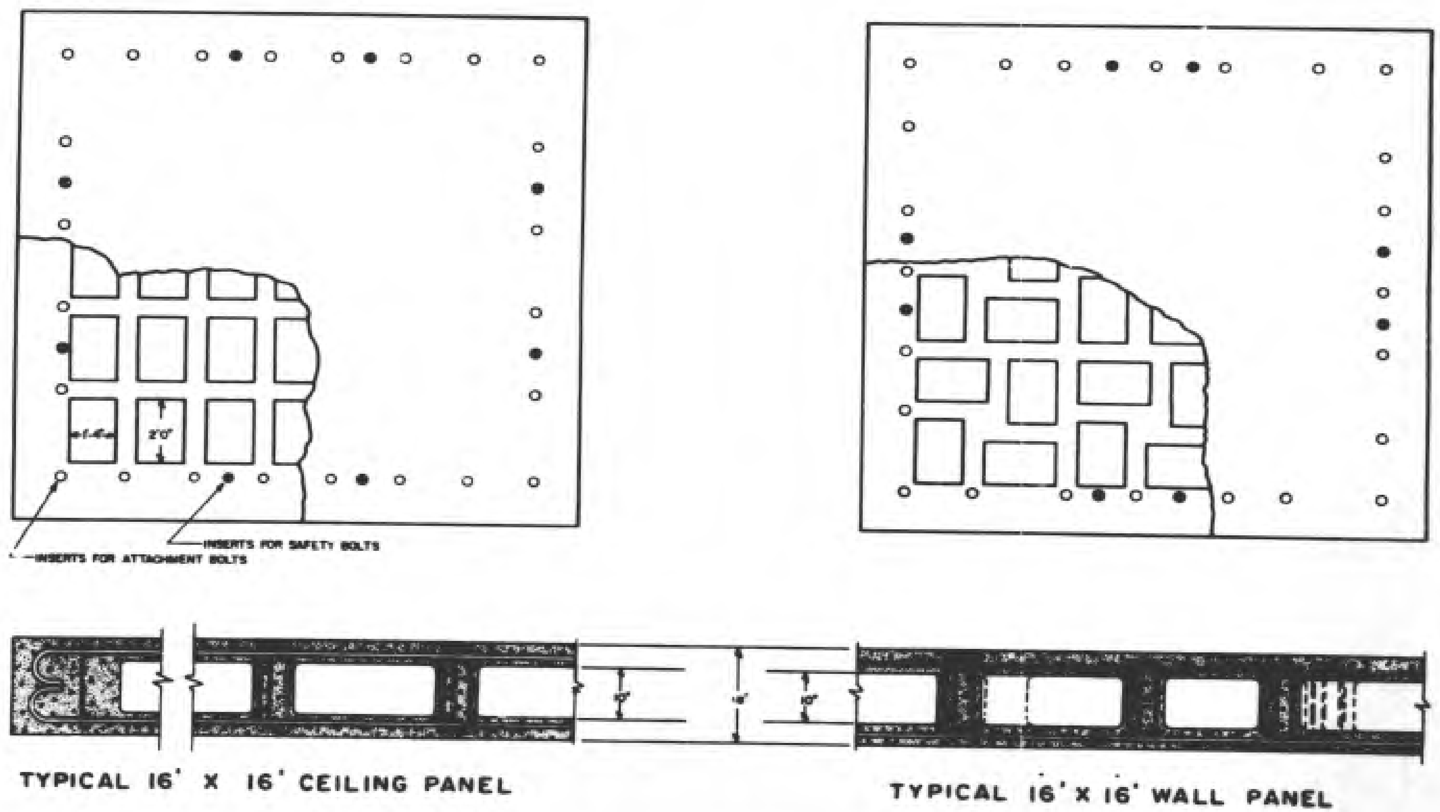


Figure 2. Sonic Fatigue Facility; Reverberation Chamber Panels

concrete panels and floor seemed logical. This is a report on the results of this experimental program. Data in the report has been taken from the study under the above mentioned Air Force contract as well as from in-house studies.

(The use of granular substances as a damping medium is often referred to as "sand damping." Experimental data on this type of damping is not readily available; consequently, the sand-damping data presented here is limited in scope but is being published as an aid in further developments which may occur.)

SECTION II

VISCOELASTIC TESTS AND DATA

Introduction

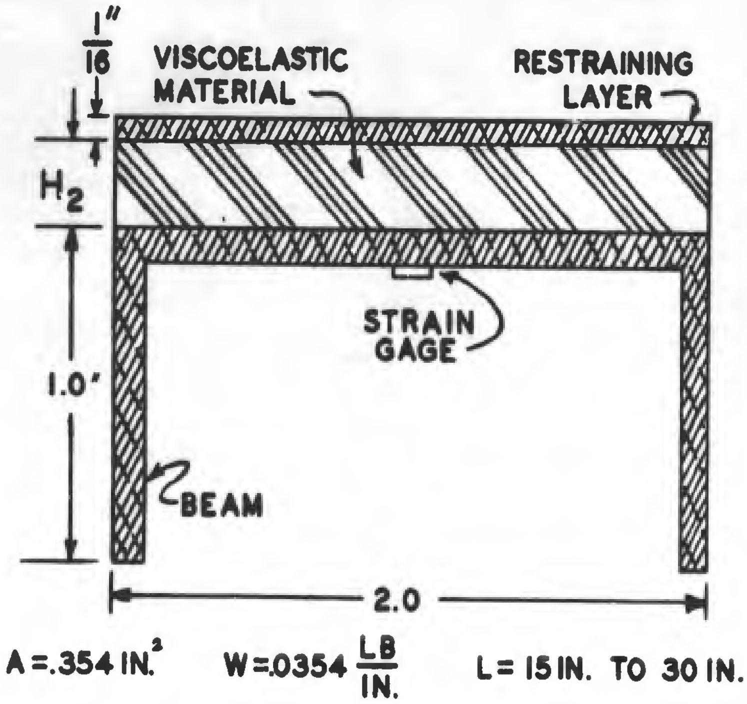
To date, the damping of such a large heavy steel structure by the use of viscoelastic material is unprecedented. Because of this, a number of questions were asked concerning its effectiveness, among them, the question of whether the loss factors calculated by the use of the theory will prove to be realistic, or whether there is a scale factor involved. A brief survey of the literature and a number of conferences with experts in this field showed that a number of tests had been performed on small, lightweight structures, and that data from these tests agreed fairly well with the theory. And, because no data on large, heavy structures could be found, a series of tests were scheduled at ASD. The configuration for the tests consisted of a beam, viscoelastic material, and a restraining layer as described earlier.

Small Beam Tests

To gain experience in performing tests of this type, the first tests in which viscoelastic material was used consisted of a small aluminum beam, the damping material, and a restraining layer, also of aluminum. (See figures 3 and 4 for dimensions and details of the beam.) These tests were initiated to get specific answers to the following questions: What is the best procedure for bonding the viscoelastic material? What bonding material is the most reliable? What difference in loss factor can be obtained for different materials? These questions could have been resolved by proceeding with the large beam tests, but it was more convenient to use smaller beams for these initial studies because of a number of materials that were available for which no manufacturers' data could be obtained. For the large beam test it was desirable to more carefully select the optimum combination of viscoelastic material and bonding agent. Also, it was expected that information could be obtained more expediently from the small beam tests concerning test techniques and the "art" of making damping measurements in general. (Unfortunately, not enough data was obtained to answer all of the above questions.)

The loss factor was evaluated according to the "logarithmic decrement" method. For this, the beam was mounted as a cantilever, the free end was deflected a given amount and released. Figures 3 and 4 show details of the arrangement of the test components. The output of a strain gage mounted at the root of the beam is recorded on a recording oscillograph; a typical trace is shown in figure 5. The loss factor is calculated by substituting data from the trace into equation 3 in the Appendix.

The data reduction technique for obtaining decay data from the viscoelastic-damped beam tests was as follows: Amplitude data, from the first cycle after release, was plotted against time for a number of cycles. As a general rule, the first part of the decay envelope in the viscoelastic test was exponential. Only the last part of the curve, to zero amplitude, showed the amplitude decayed as a linear function of time. Between these parts of the curve there is a transition region (figure 5). In all cases, the loss factors were computed using data from the initial part of the curve, where the amplitude decayed as an exponential function of time.



SECTION A-A

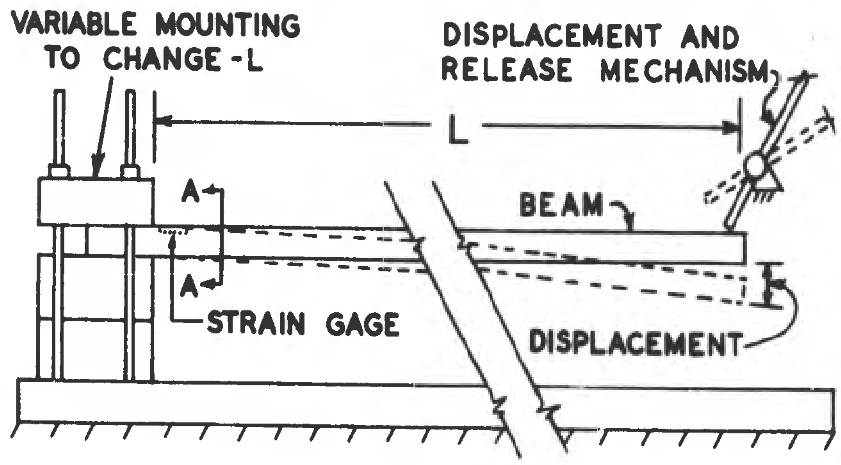
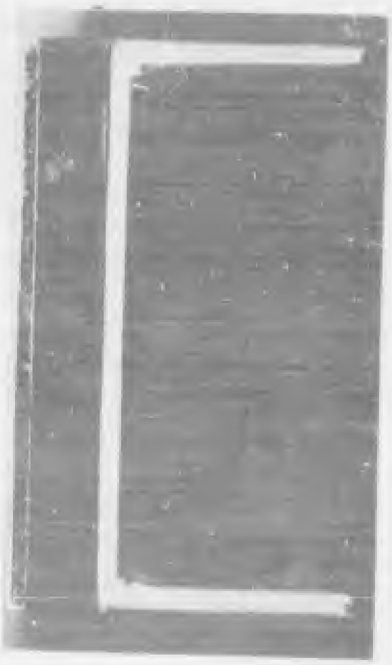


Figure 3. Small Beam in Test Position (Lower Drawing); Cross Section (A-A) Above



TEST BEAM (END VIEW)

DEFLECT AND RELEASE MECHANISM

BEAM IN TEST POSITION

Figure 4. Test Equipment and Small Beam in Test Position

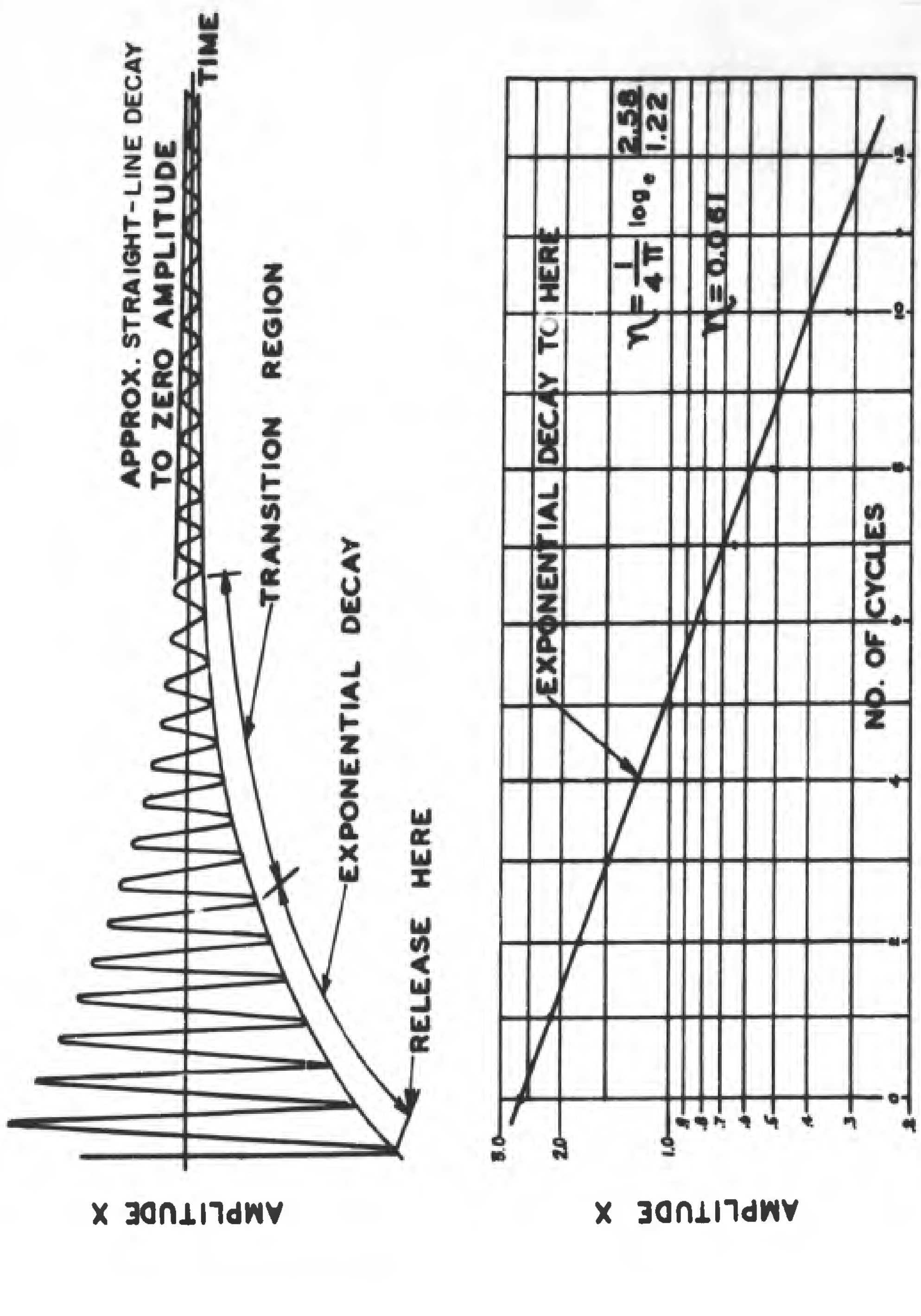


Figure 5. Typical Decay Curve

The length of the beam was varied by changing the mounting point. This, in effect, changes the frequency of decay and allows loss factors to be calculated for different frequencies. Frequencies between 20 and 200 cps were of primary interest. At high strain levels, the loss factor of the viscoelastic material may vary with the amplitude of the strain (ref 2). The effect of this parameter was checked.

The tests were performed by deflecting the free end of the beam a given amount, releasing it, then allowing the beam to oscillate freely while the signal from the strain gage was being recorded. Varying the strain in the material was accomplished by varying the amplitude of deflection. A number of different viscoelastic materials, bonding agents, and combinations thereof were tested, and the results are shown in figures 6 and 7. Because materials data could not be obtained on all the materials tested, the only means of comparison was a test of the materials in similar configurations. This meant using viscoelastic material of the same thickness for each test.

Large Beam Tests

In the large beam tests, an I-beam of the dimensions shown in figure 8 was used. Details of equipment and arrangement are shown in figure 9.

Loss factors for this configuration were calculated by using decay time measurements, and a bandwidth measurement. The decay measurement was taken in the following manner: The beam was mounted as a free-free beam with the support points at the node points of the beam for the first mode. An electro-dynamic shaker applied a force which varied as a sinusoidal function of time to the center of the beam. The frequency was the resonant frequency of the beam for this configuration. The amplitude of the force was determined by letting the acceleration at the end of the beam assume certain values. The purpose of this was to allow repeat runs to be made at the same strain levels and also to afford an opportunity to observe any variation in the loss factors due to a difference in strain levels. Once this condition was attained the current to the shaker was cut-off and the beam and shaker were allowed to decay to zero amplitude. A strain gage located at the center of the beam registered decay information. The loss factor was calculated in the same manner as it was for the small beam test.

The bandwidth was measured by assuming the same initial condition as described above. In addition, the amplitude at the center of the beam was recorded at the resonant frequency point. By holding the current to the shaker constant, the frequency was varied a small amount to each side of the resonant frequency in small increments. The amplitude was recorded at each increment and the data were plotted. See figure 10 for a typical plot. The loss factor was computed from equation 5 (Appendix). The results using different materials, bonding agents, and combinations thereof are given in tables 1, 2, and 3.

Table 1

Comparison of Measured Values of Loss Factors
(4 Runs) for Different Amplitudes for Large
I-Beam. Material: A. Adhesion: A.

AMPLITUDE		SMALL	MEDIUM	LARGE
Loss Factors $f_n = 126$ cps	DECAY METHOD	.024 .027	.024	.021

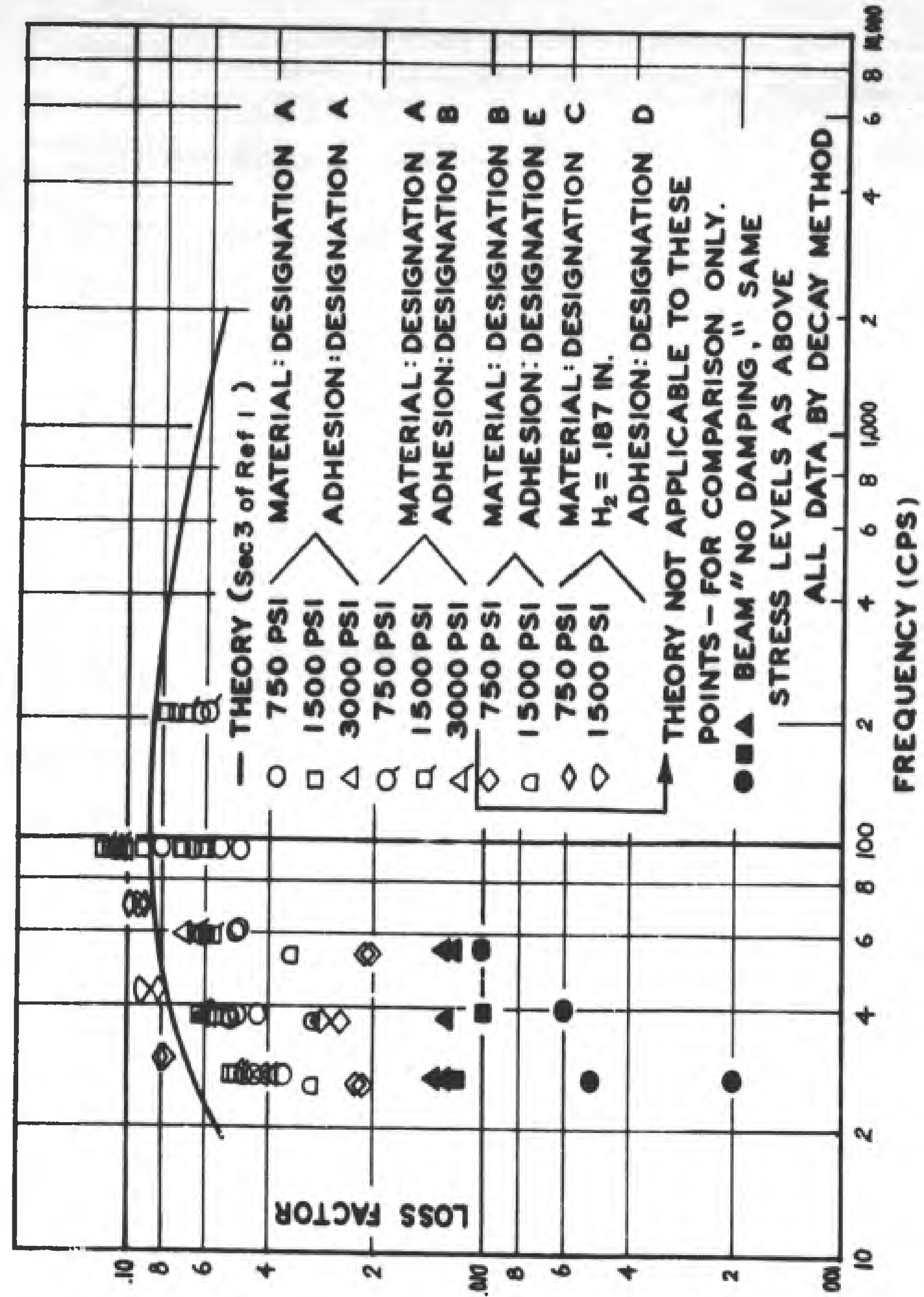


Figure 6. Loss Factor vs. Frequency; Comparison of Calculated and Experimental Data for Small Beam Tests; $H_2 = 0.250$ In.

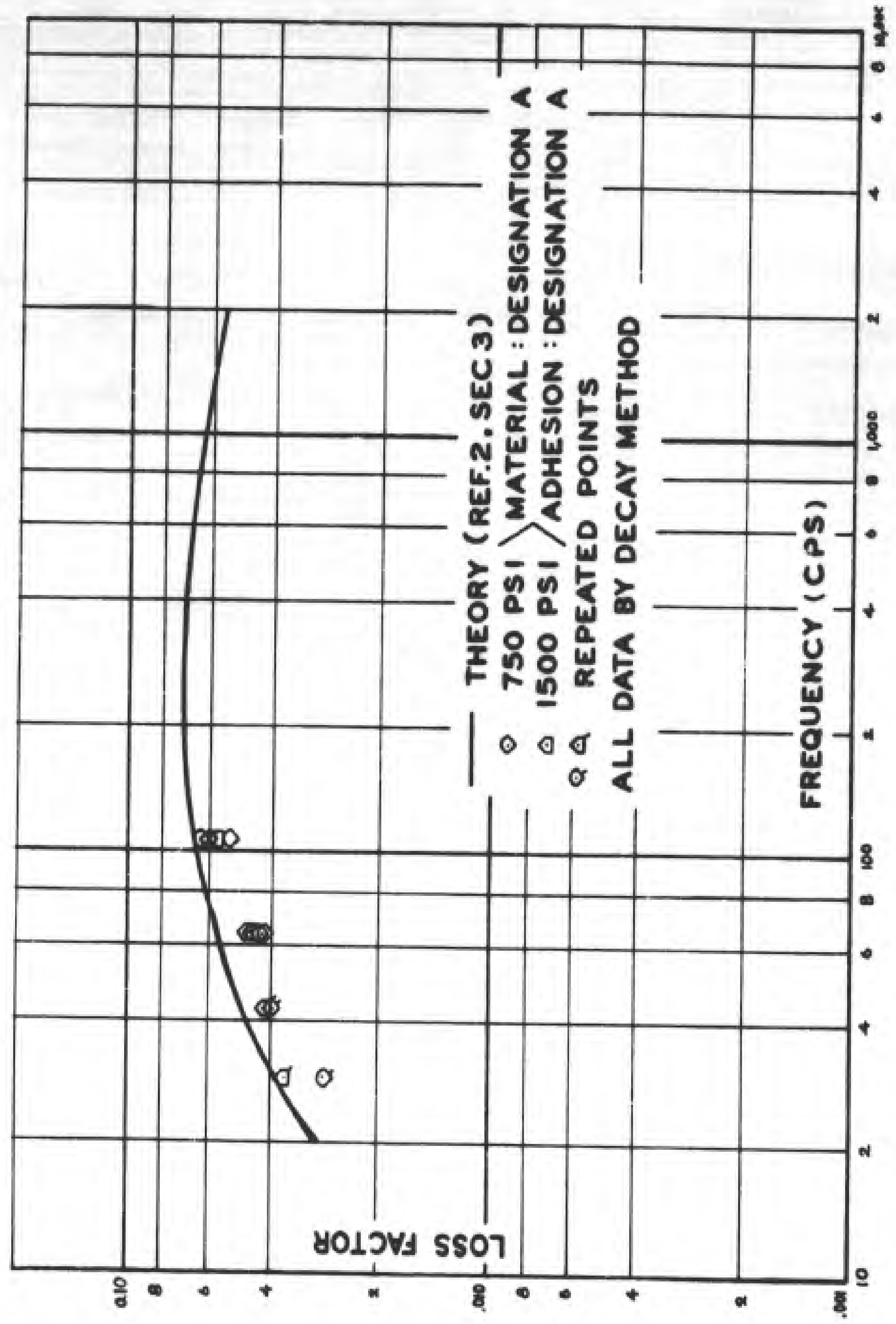
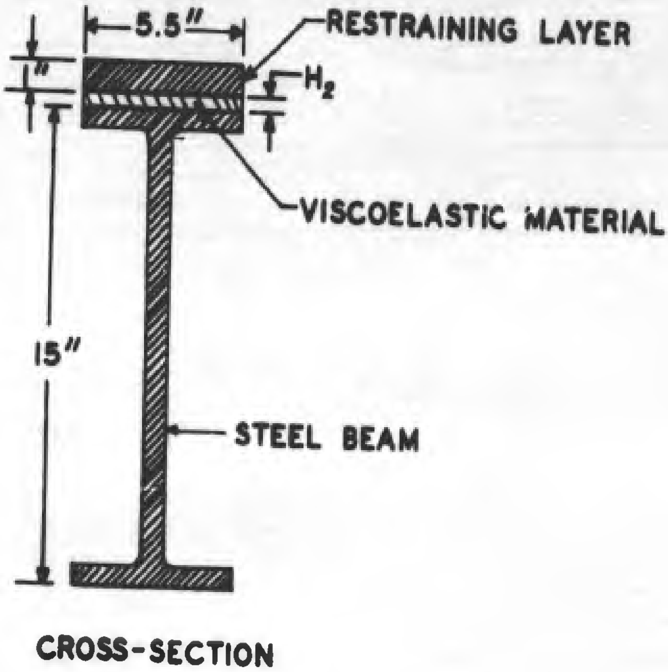


Figure 7. Loss Factor vs. Frequency; Comparison of Calculated and Experimental Data for Small Beam Tests; H_2 = 0.125 In.



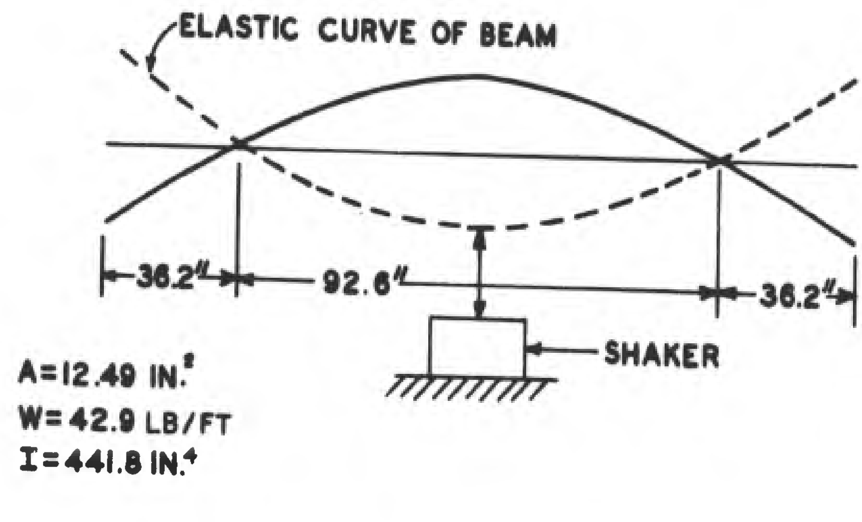


Figure 8. Large Test Beam

BEAM (IN POSITION)

BEAM (END VIEW)

Figure 9. Large Beam in Test Position

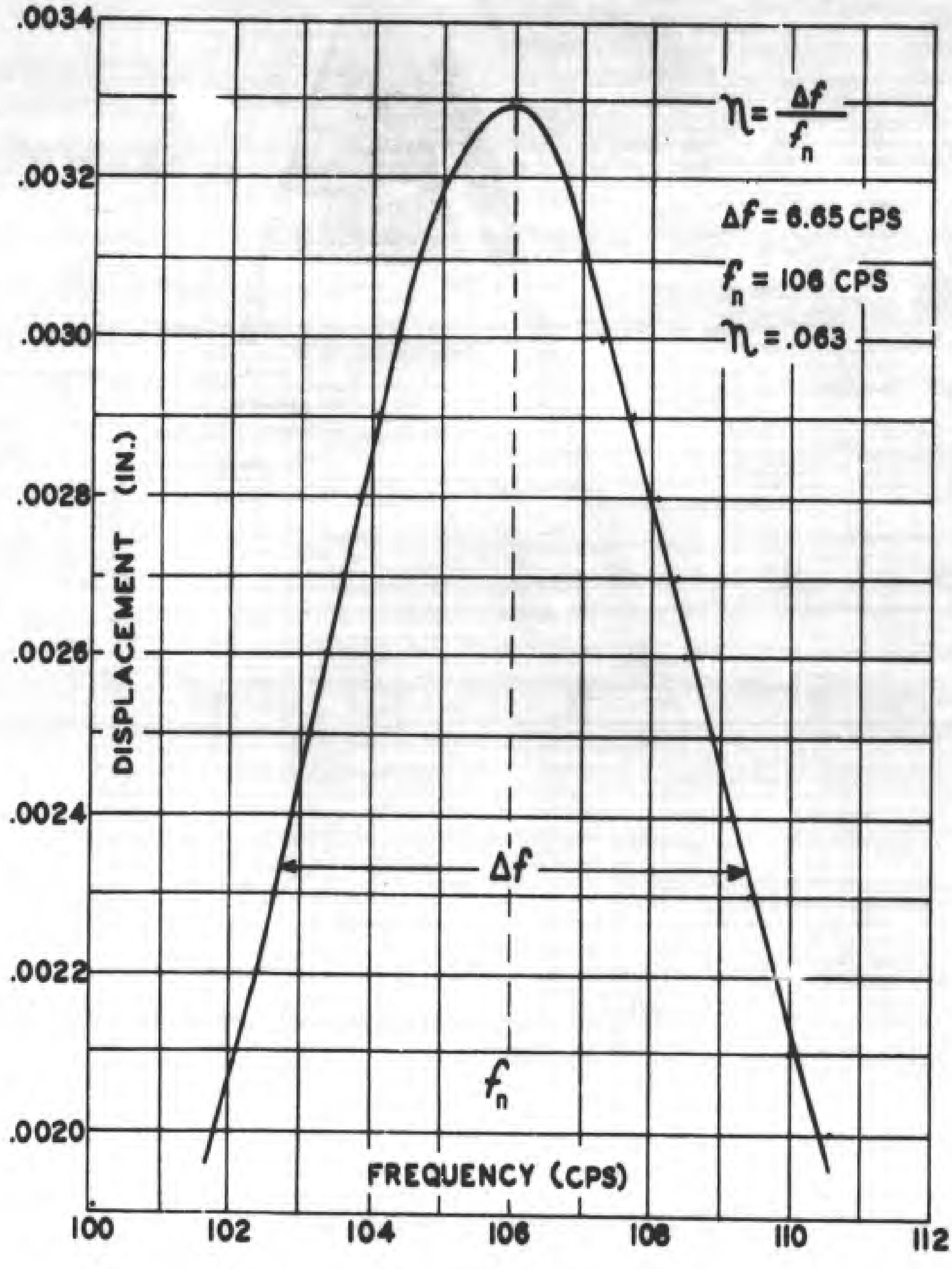


Figure 10. Typical Response Curve; Displacement vs. Frequency

Table 2

Comparison of Measured Values of Loss Factors
for Different Values of Initial Acceleration
and Shakers for Large I-Beam. Material: A.
Adhesion: B. f_n = 126 cps.

TECHNIQUE	SHAKER \ ACCELERATION (g's)	1	2	3	4	6	8
DECAY METHOD	125 lbs	.033	.033	-	.031	.033	-
	650 lbs	.034	.034	-	.035	-	.035
BANDWIDTH METHOD	125 lbs	-	.038	.037	.035	.037	-
	125 lbs	-	-	-	.038	-	-

Loss Factor as calculated by theory: η = 0.039 f = 126 cps Material: A

Table 3

Comparison of Measured Values of Loss Factors
for Large Beam for Different Values of
Initial Acceleration. Material: D. Adhesion: C
f_n = 148 cps.

ACCELERATION (g's)	1	2	4	6
DECAY METHOD	.021	.021	.022	.023
BANDWIDTH METHOD		.019	.021	.019

Sandwich-Panel Beam Tests

The viscoelastic material for the damping system of the main test chamber is attached to the steel beams and girders by the use of "sandwich plates." A sandwich plate consists of two steel plates between which a sheet of viscoelastic material is bonded. The steel plates are then bolted to the beams or girder and damping beam (figure 1). Because this method of attachment is unique, model tests were made to see if a change in loss factor would occur between this configuration and that of the material bonded directly to the beam and restraining layer. Figure 11 shows the dimensions of the beam for this test, and figure 12 shows other details of the test.

Measurements were made by the decay, bandwidth, and energy methods to enable the comparison of data between the three testing methods. The energy method allows measurement of the data under truly steady-state conditions. The beam was forced to oscillate at its natural frequency. The amplitude of the force was set according to the acceleration at the end of the beam. These acceleration values were fixed in order to repeat data at

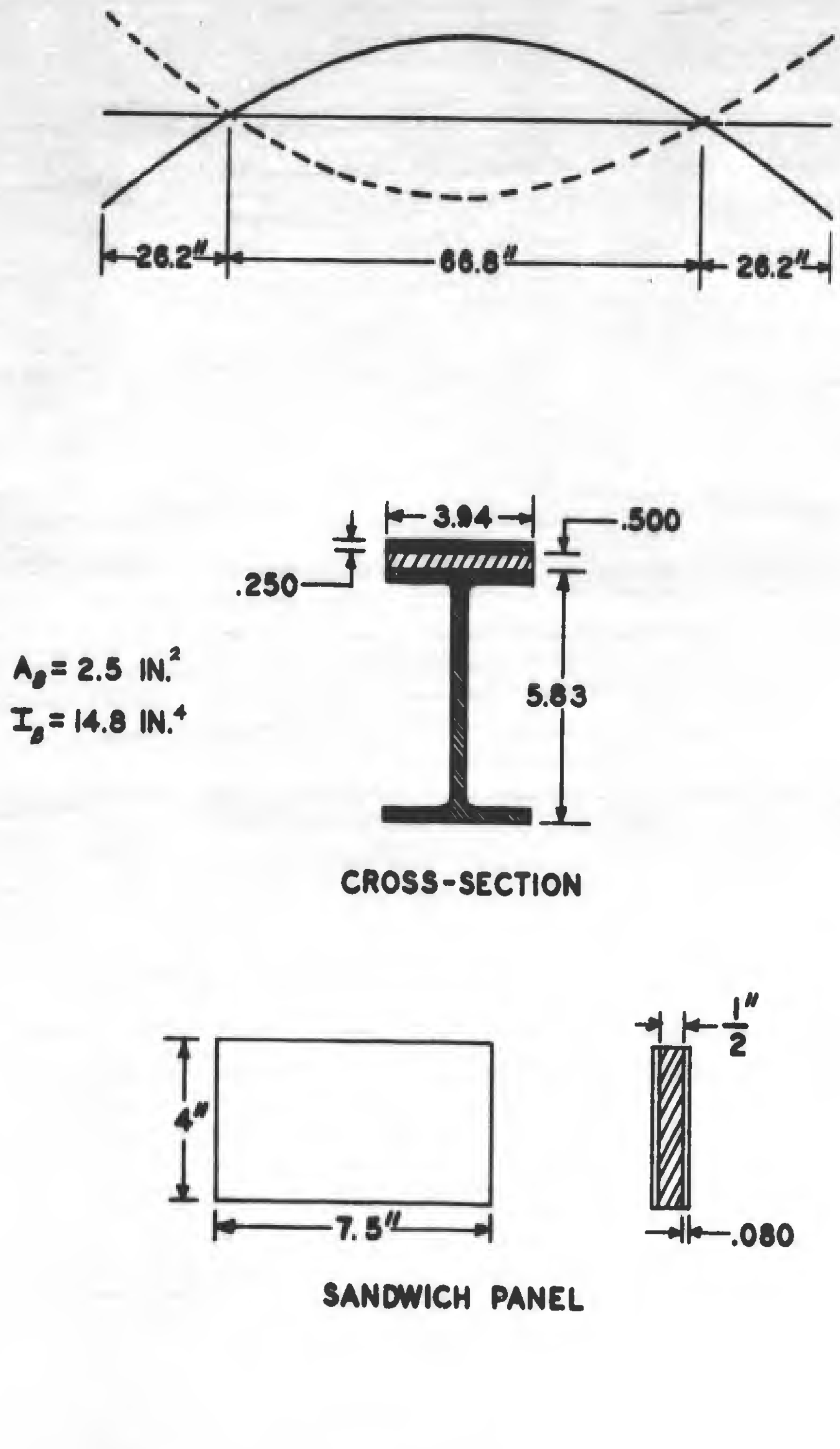


Figure 11. Sandwich-Panel Test Beam (Schematic)

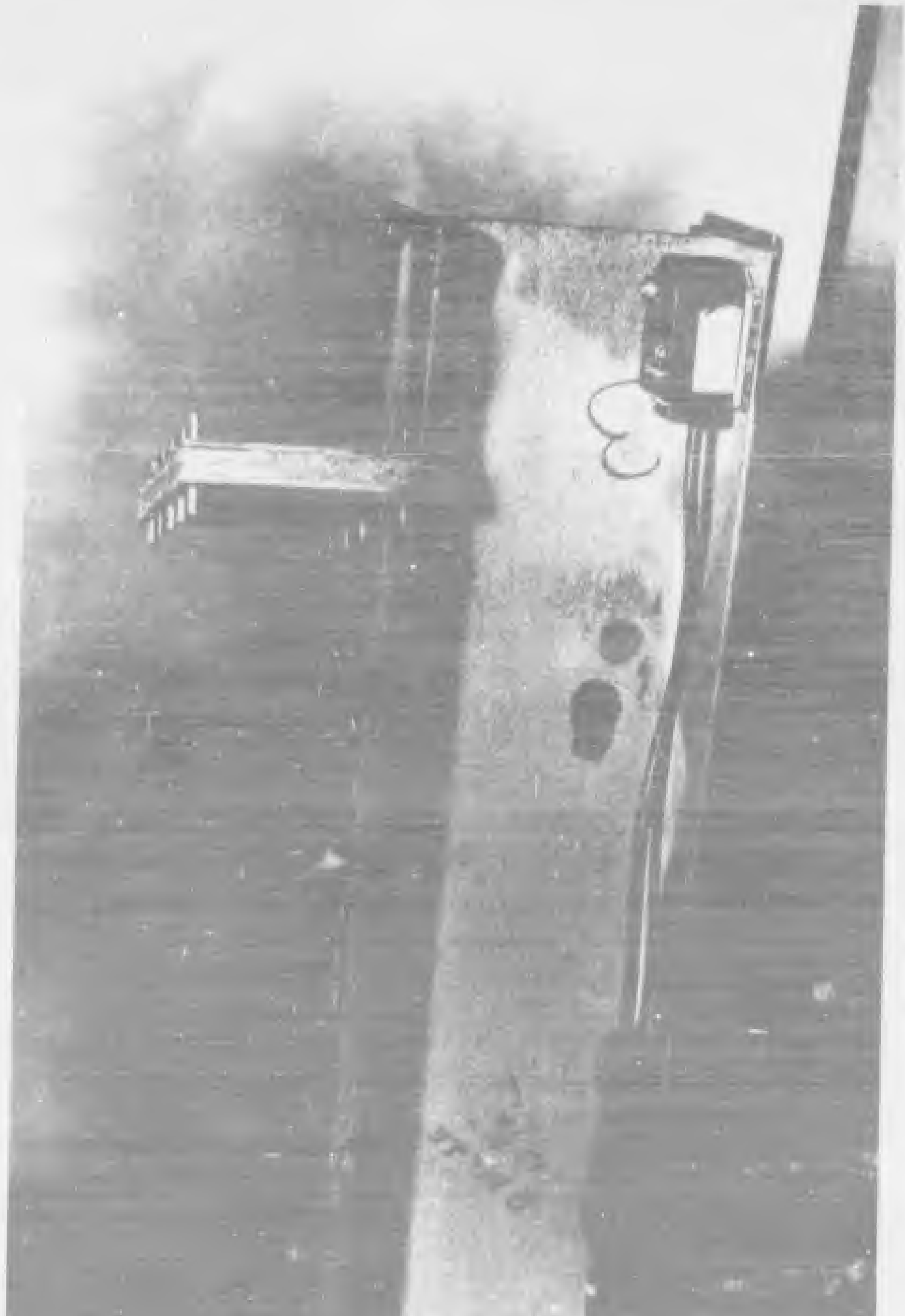


Figure 12. Sandwich-Panel Test Beam

the same strain level. A calibrated strain gage link was attached between the shaker and the beam to measure the amplitude of the force input to the beam. The mass of the system was found by weighing the beam, and the natural frequency was known from strain gage information. The amplitude at the center of the beam was measured. This was also the displacement through which the force acted. Since the system was operating at its resonance point the phase angle was 90°. (This phase angle of 90° has been checked by measurement and found to be accurate if the resonance point is very carefully determined by selecting the frequency for maximum amplitude.) With this information and equation 16 (Appendix) the loss factor of the system can be computed.

Damping measurements were made with the beam in both the horizontal and vertical positions and also in the first and second modes. Loss factors are given in tables, 4, 5, and 6.

Table 4

Comparison of Loss Factors for Different Acceleration Levels and Testing Methods for Configuration with Viscoelastic Sandwich Panels Bolted to Beam and Restraining Layer. Material: E. Adhesion: C. Beam Position: Horizontal.

BEAM POSITION	HORIZONTAL				VERTICAL
FREQUENCY	108 cps 1ST MODE			291 cps 2ND MODE	1ST MODE
ACCELERATION (g's)	DECAY METHOD	ENERGY METHOD	BANDWIDTH METHOD	BANDWIDTH METHOD	DECAY METHOD
1 2 4 6	.062 .061 .063 .064	.062 .063 .063 .068	.070 .073	~ .090 ~ .091	.062 .062 .065 .066

Table 5

Comparison of Loss Factors for Configuration as Given for Table 4 Except Material Is Bonded Directly to Beam and Restraining Layer.

FREQUENCY	108 cps		
ACCELERATION (g's)	DECAY METHOD	ENERGY METHOD	BANDWIDTH METHOD
1 2 4 6	.058 .058 .062	.064 .061 .066	.063 .061

Table 6

Calculated Loss Factor Values for Configuration as Given in Table 4.

FREQUENCY (cps)	108	291
LOSS FACTOR	.080	.080

Concrete-Beam Tests

Two series of tests have also been conducted using viscoelastic material and concrete bars (ref 2). In the first of this series a steel restraining layer and concrete bars covered with viscoelastic material were used. See figure 13 for the detailed dimensions of the test bars. Table 7 gives the loss factors that were computed from bandwidth measurements for this test.

Table 7

Loss Factor vs. Frequency for Reinforced-Concrete Model Beam. Material: C. Adhesive: D.

FREQUENCY (cps)		270	690	1310	2000
RESTRAINING LAYER THICKNESS (mm)	2	.083	.081	.054	.036
	.7	.034	.020	.021	.029

In the second test the reinforcing rods were covered with viscoelastic material and cast directly into the concrete. See figure 14 for detailed dimensions of the test bar, and table 8 for results of the test.

Table 8

Loss Factor vs. Frequency for Concrete Model Beams with Viscoelastic-Coated Steel Reinforcement Rods. Material: F.

FREQUENCY (cps)		250	680	1280	1990
LAYER THICKNESS (mm)	2.5	.024	.013	.016	.016
	5.0	.028	.015	.015	.015

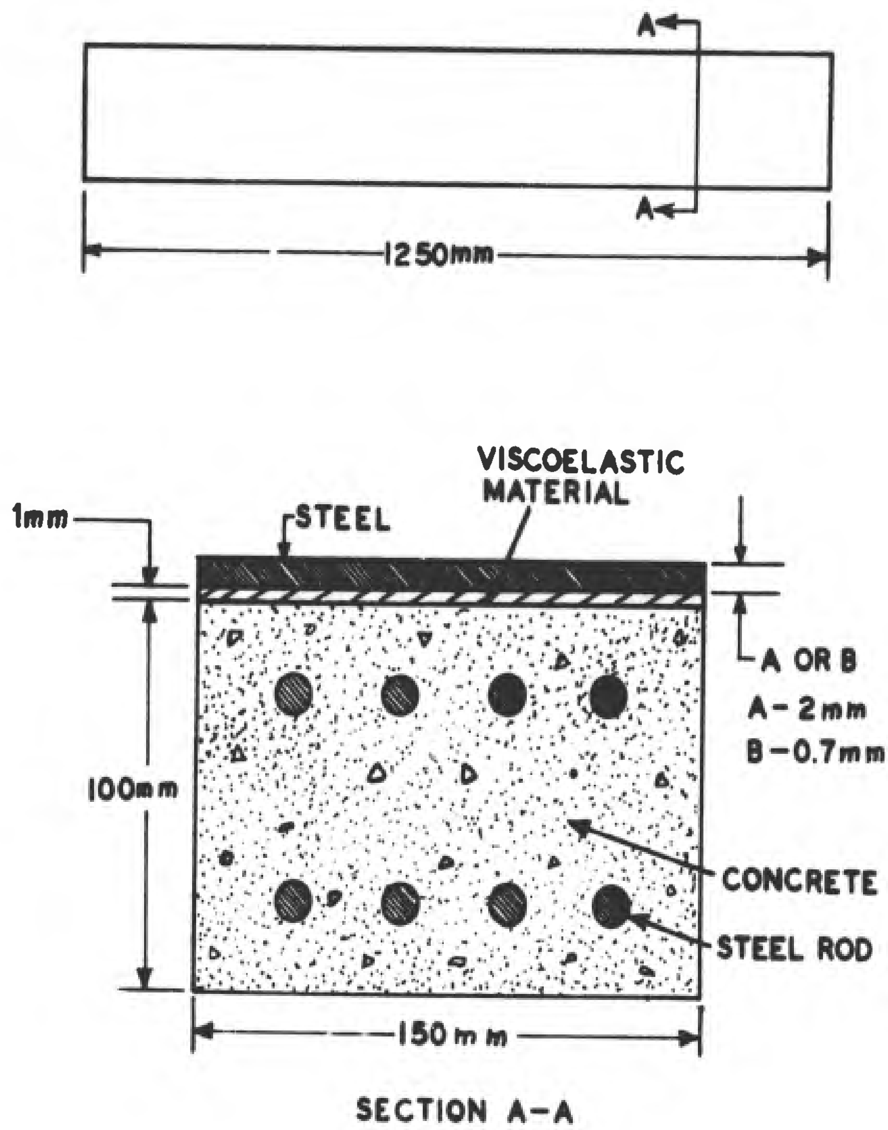


Figure 13. Concrete Test Bar with Viscoelastic Covering for Damping

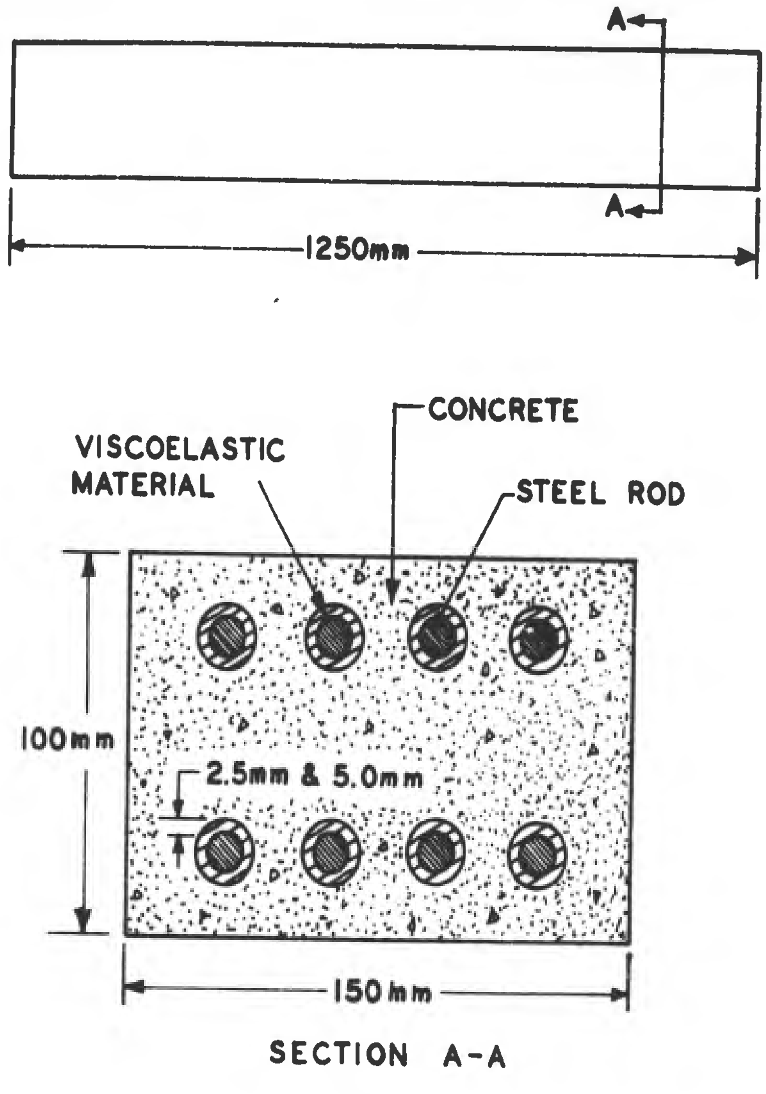


Figure 14. Concrete Test Bar with Viscoelastic-Covered Steel Reinforcement Rods

SECTION III

SAND-DAMPING TESTS AND DATA

Concrete-Beam and -Panel Tests

The wall, ceiling panels, and floor of the main test chamber are damped by sand. This has been described previously. Sand damping is not new, but it is a system for which calculation of loss factors for a given configuration is difficult. Published data were not available. Therefore, to determine if the loss factors for the panels were of sufficient magnitude, damping tests were performed (ref 2). These tests were performed on scaled concrete beams and one panel, in which the ratio of sand to concrete was 1:4. Figure 15 gives the detailed dimensions of the beam and panel. Loss factor measurements for the beam and panel under various conditions are given in tables 9, 10, 11, and 12.

Steel Beam Tests with Six Boxes

The damping of a steel beam undergoing flexural vibrations from the use of sand was also investigated at ASD in some detail. The purpose of the investigation was to determine if damping could be obtained with gravel at the lowest expected natural frequency of the large concrete panels. This frequency calculation was about 40 cps. There was some doubt expressed about obtaining the required damping at this low value of frequency. Data at this frequency could not be obtained from the model panel because its lowest natural frequency was about four times that of the full-size panel.

The damping tests were performed using a "wide-flanged" steel beam that was mounted as a free-free beam in both the horizontal and vertical positions (figures 16 and 17). Six steel boxes were bolted to one surface of the beam. The box length was the same as that for a full-size panel. The weight of gravel was a maximum of 30 percent the weight of the beam and steel boxes. The size and length of the beam were such that when mounted as a free-free beam the lowest natural frequency was about 40 cps. Tests were made using 10, 20, and 30 percent gravel to determine loss factor variation as a function of ratio of gravel-to-beam weight. Acceleration levels were also varied to determine loss factor variation. Gravels of three different sizes were also used. Loss factors are given in figures 18, 19, 20, 21, 22, and 23. The decay, bandwidth, and energy methods were the testing procedures used to enable the comparison of data by the three methods.

Steel Beam Tests with Large Box

Tests were also performed to determine loss factor variation as a function of height of gravel in the box. One large box was bolted to the center of the steel beam (figure 24). Gravel height was varied and the loss factors were measured as previously described. Figures 25 and 26 give results of the test.

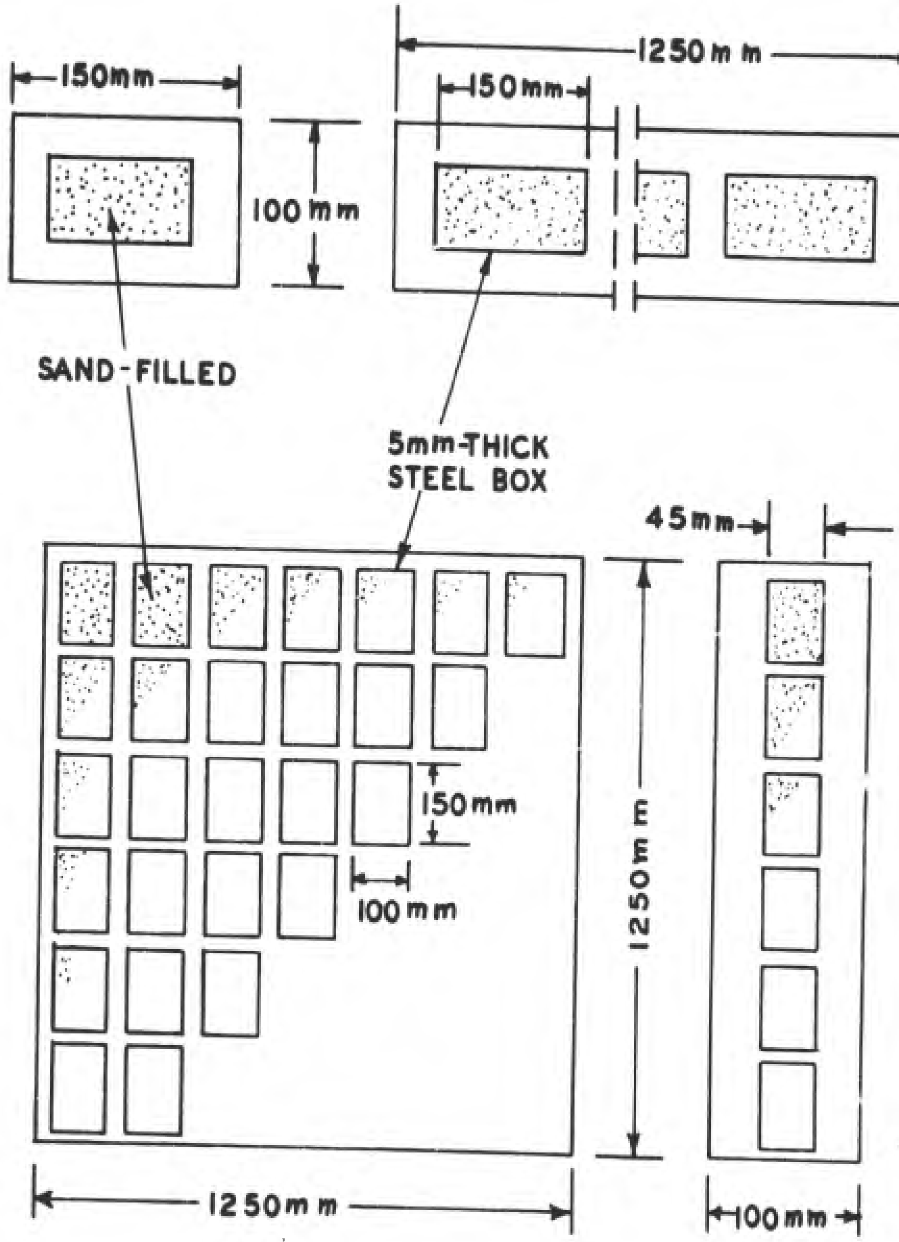


Figure 15. Concrete Test Bar and Panel; Sand-Filled

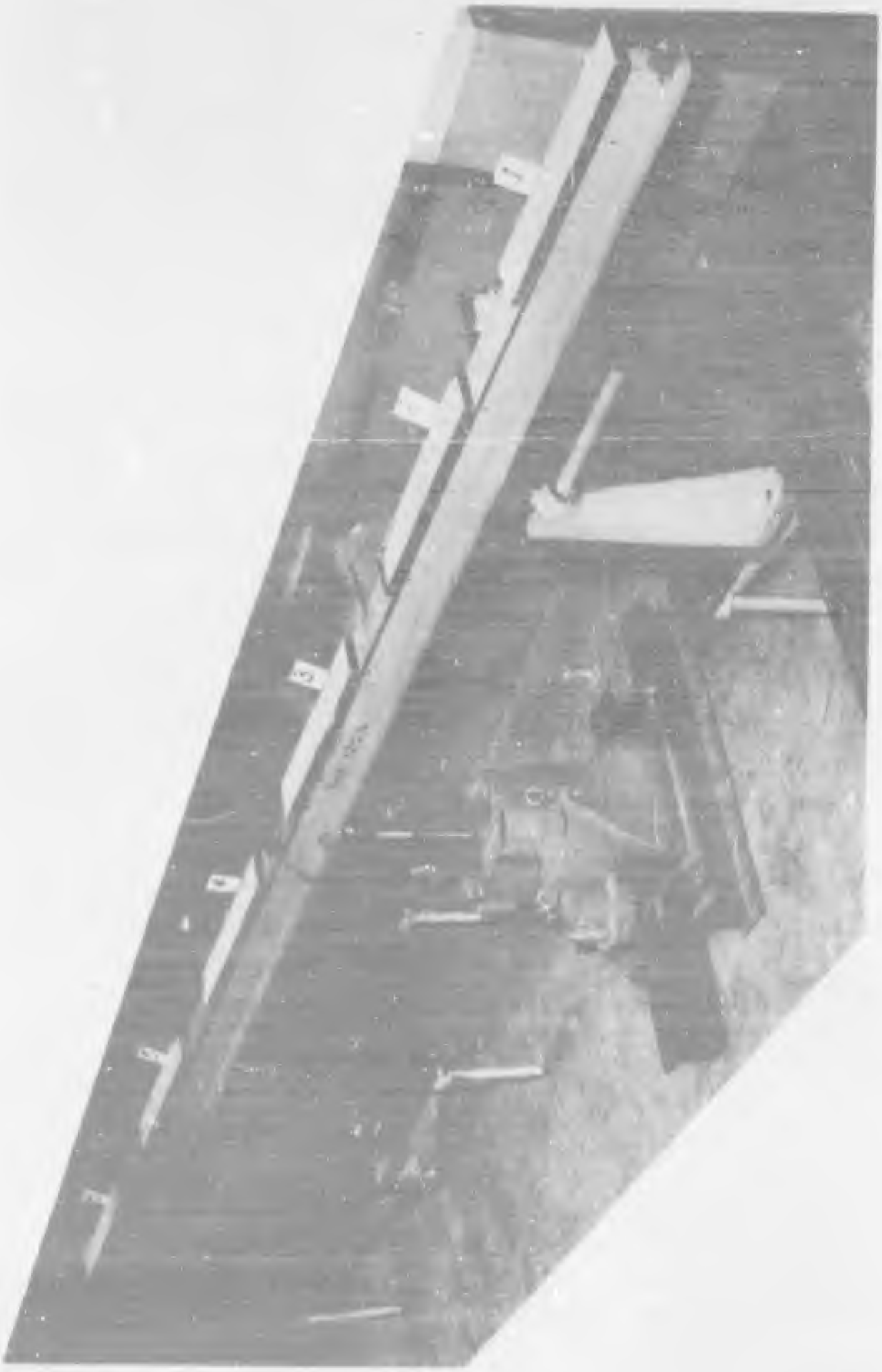


Figure 16. Sand-Damped Beam with Six Boxes in Horizontal Test Position

Table 9

Loss Factor vs. Frequency for Reinforced Concrete Model Beam in Horizontal and Vertical Positions with Constant Acceleration of 0.1 g's; Sand-Damped.

FREQUENCY (cps) / BEAM POSITION	280	690	1220	1830
LOSS FACTOR (HOR.)	.03	~.05	~.06	.05
LOSS FACTOR (VERT.)	.023	~.2	~.17	

Table 10

Loss Factor vs. Acceleration for Reinforced Concrete Model Beam in Horizontal and Vertical Positions with Constant Frequency of 280 cps; Sand-Damped.

ACCELERATION (g's) / BEAM POSITION	.1	1	2
LOSS FACTOR (HOR.)	.03	.08	.17
LOSS FACTOR (VERT.)	.023	.04	.06

Table 11

Loss Factor vs. Frequency for Reinforced Concrete Model Beam; No Damping Treatment

FREQUENCY (cps)	250	700	1290	1700
LOSS FACTOR	.014	.011	.01	.009

Table 12

Loss Factor vs. Frequency and Acceleration for Reinforced Model Panel in Horizontal and Vertical Positions; Sand-Damped

BEAM POSITION AND ACCELERATION (g's) \ FREQUENCY (cps)		170	270	880
LOSS FACTOR HORIZONTAL	.1 1	.016 .075	.029	.078
LOSS FACTOR VERTICAL	.1 1	.015 .041	.078	.066

Figure 17. Sand-Damped Beam with Six Boxes in Vertical Test Position

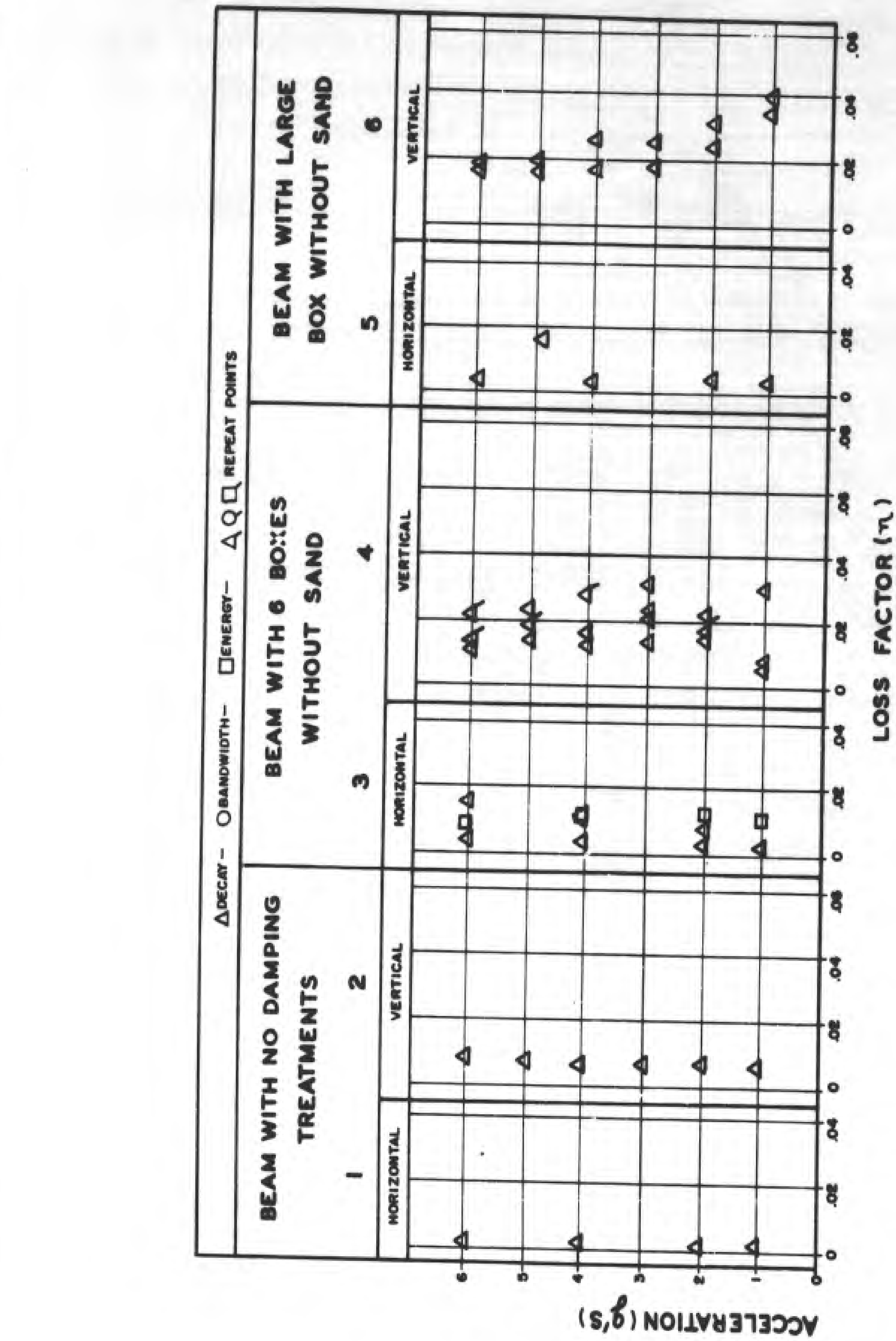


Figure 18. Loss Factor vs. Acceleration for Beam with No Damping Treatment and Beam with Six Boxes without Sand; Also Beam with Large Box without Sand; Horizontal and Vertical Positions; First Mode

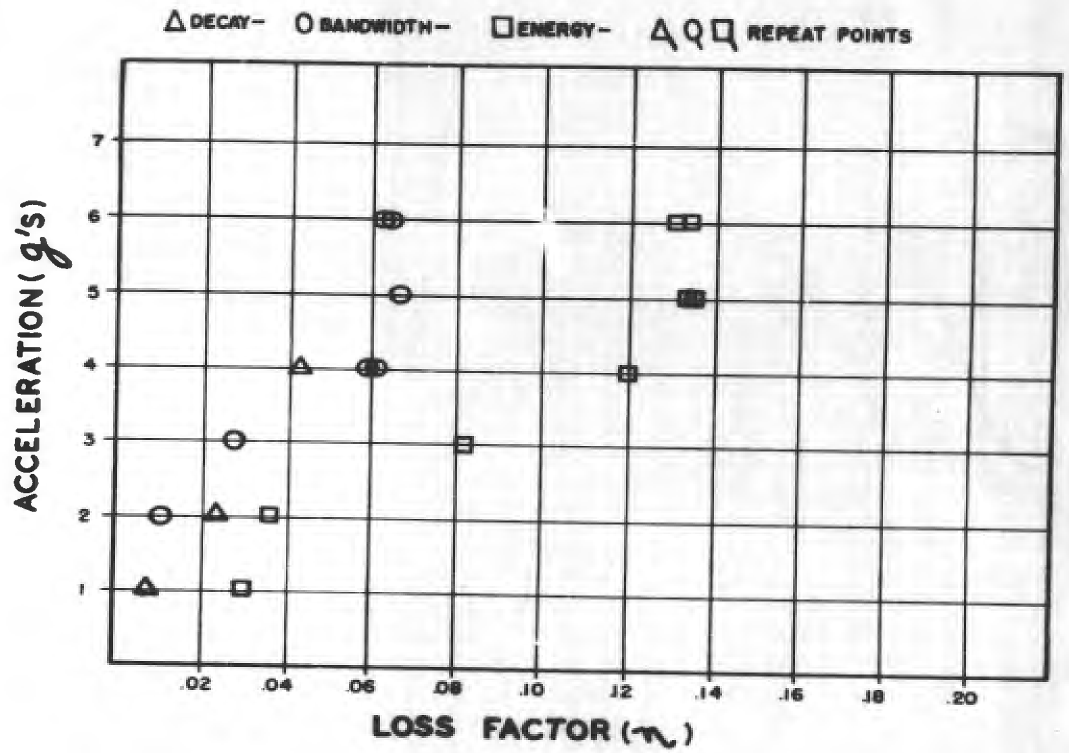


Figure 19. Loss Factor vs. Acceleration for Beam with Six Boxes; 10% Crushed Rock and Gravel; Horizontal Position; First Mode

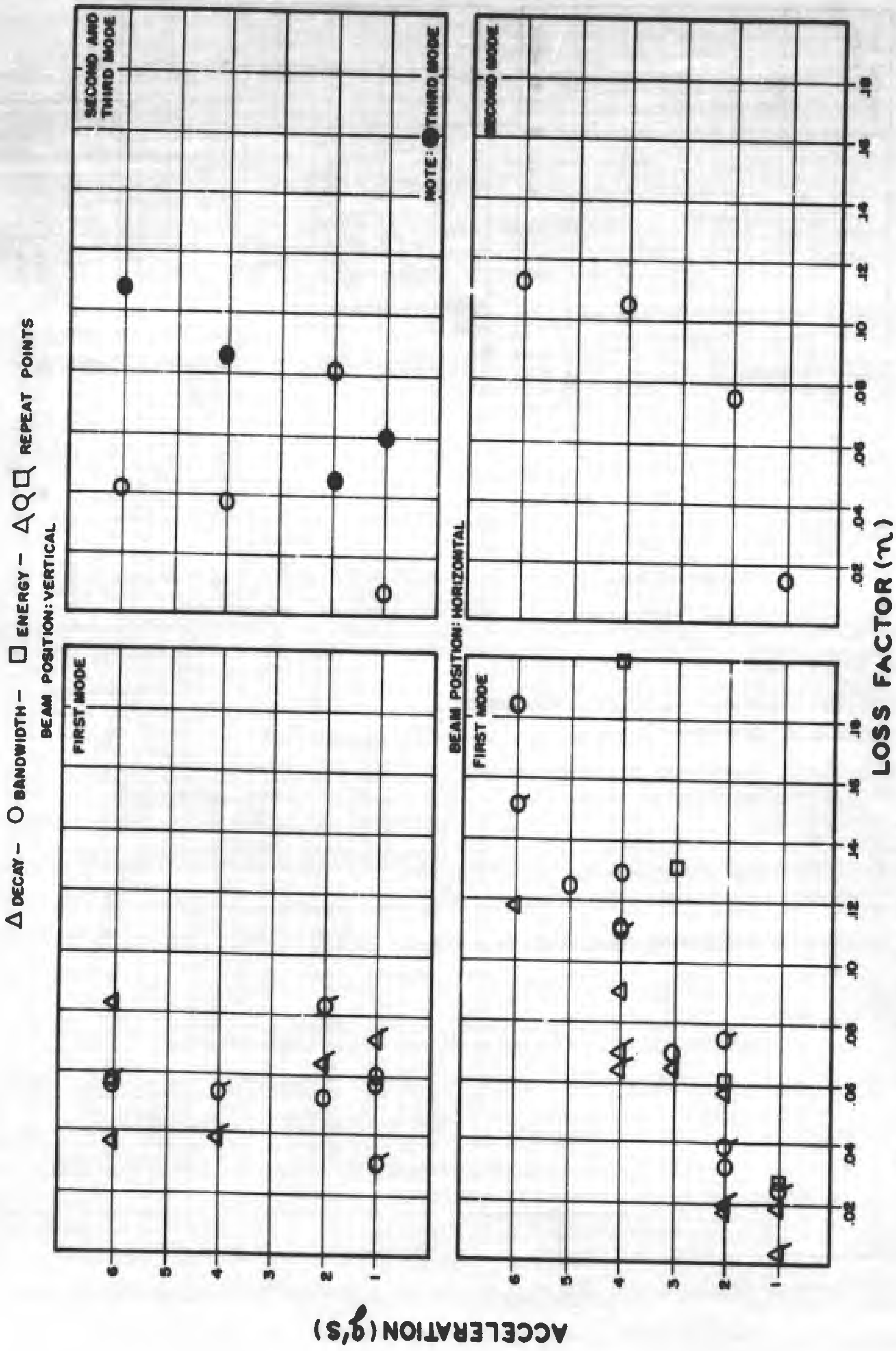


Figure 20. Loss Factor vs. Acceleration for Beam with Six Boxes; 20% Crushed Rock and Gravel; Horizontal and Vertical Positions; First, Second, and Third Modes

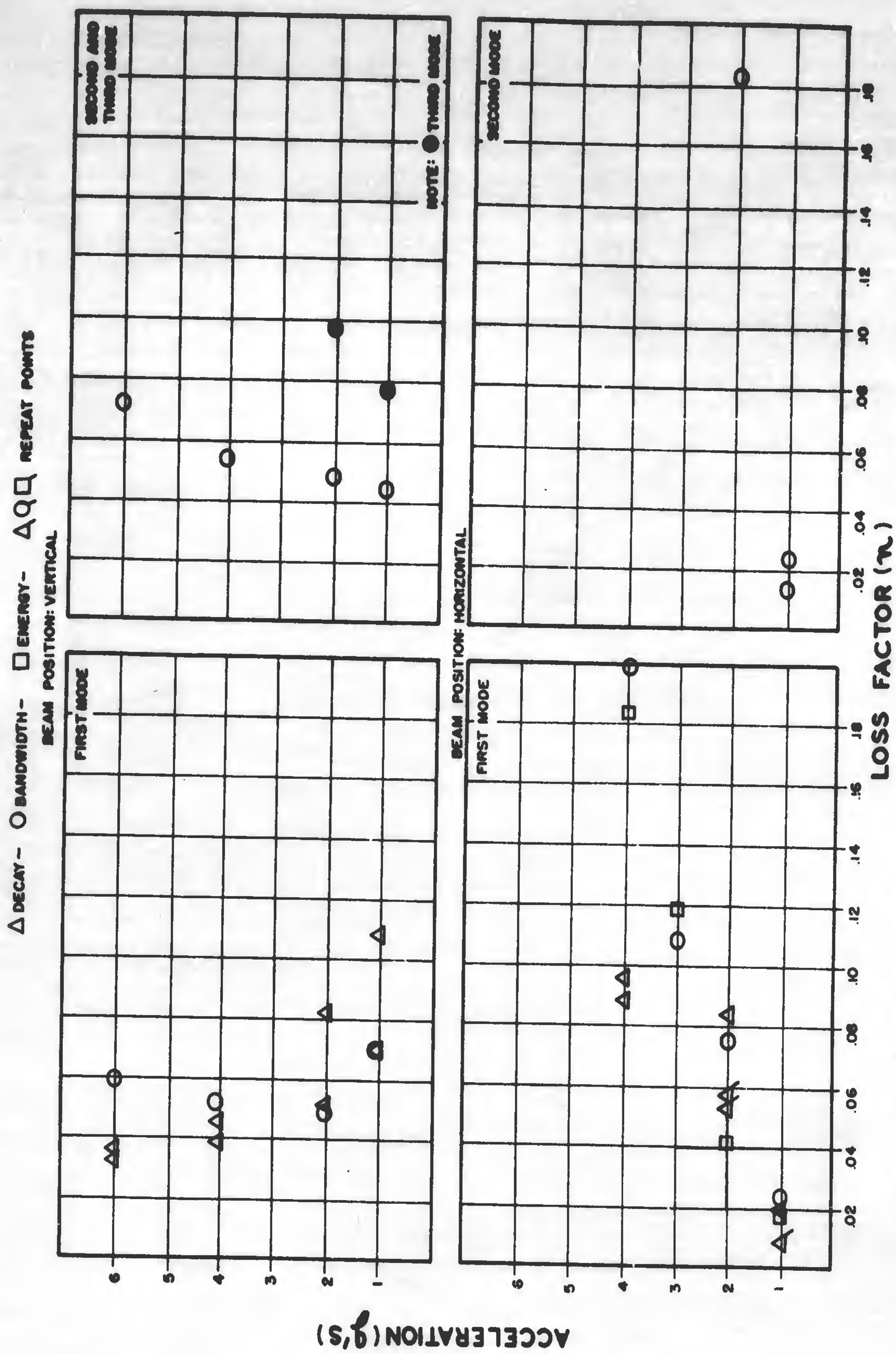


Figure 21. Loss Factor vs. Acceleration for Beam with Six Boxes; 30% Crushed Rock and Gravel; Horizontal and Vertical Positions; First, Second, and Third Modes

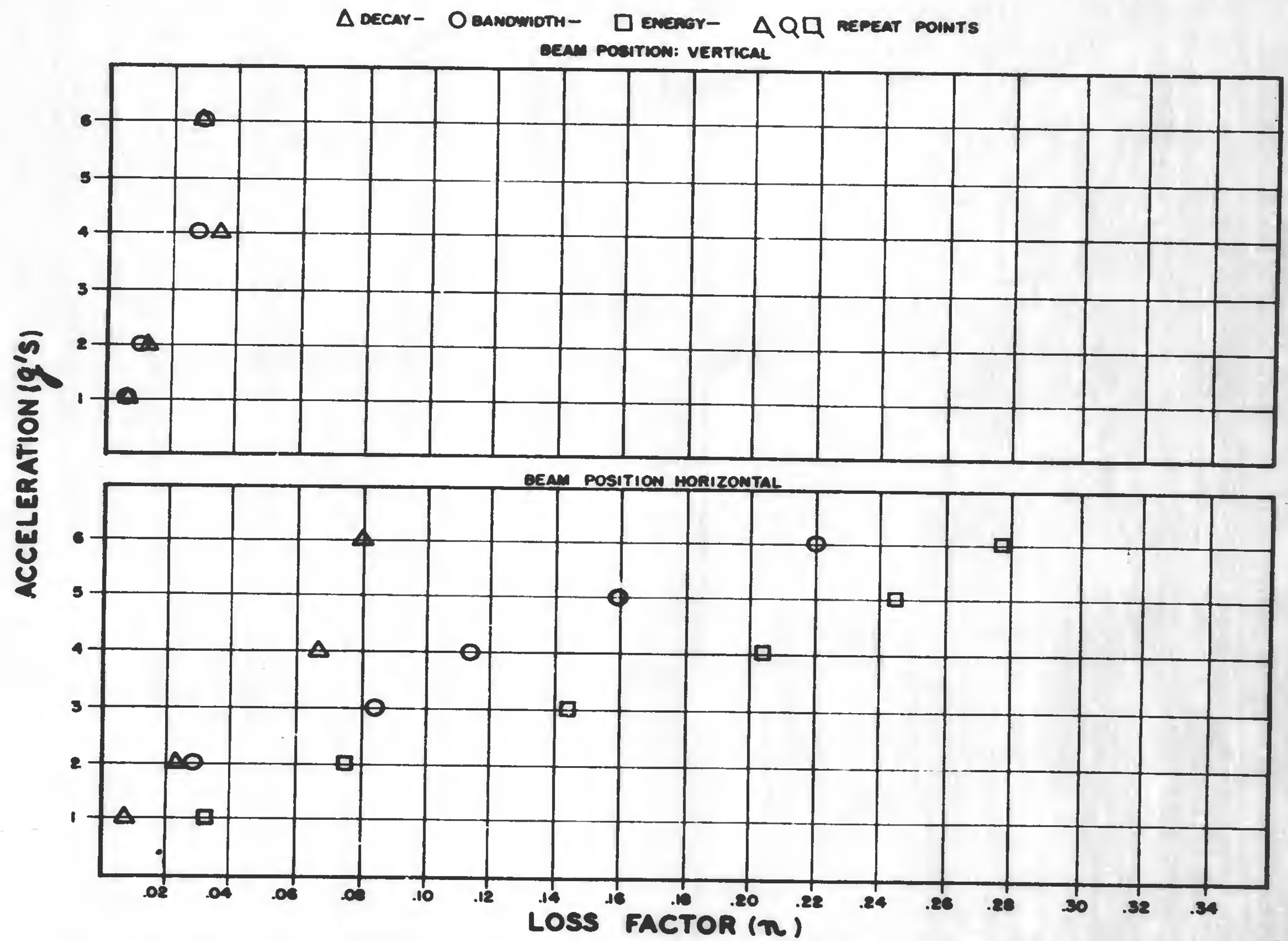


Figure 22. Loss Factor vs. Acceleration for Beam with Six Boxes; 20% Pea Gravel; Horizontal and Vertical Positions; First Mode

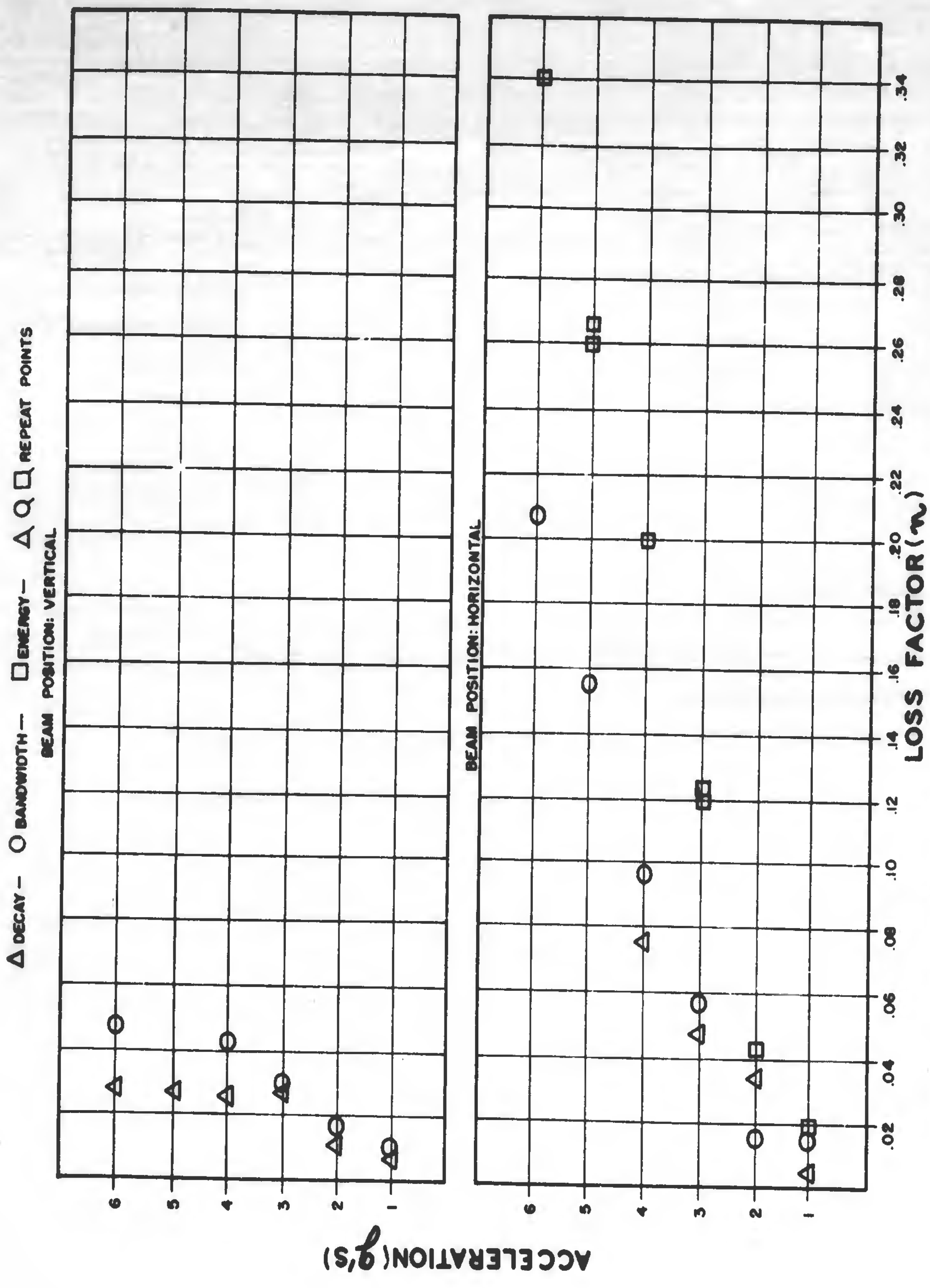


Figure 23. Loss Factor vs. Acceleration for Beam with Six Boxes; 20% Washed Mix; Horizontal and Vertical Positions; First Mode

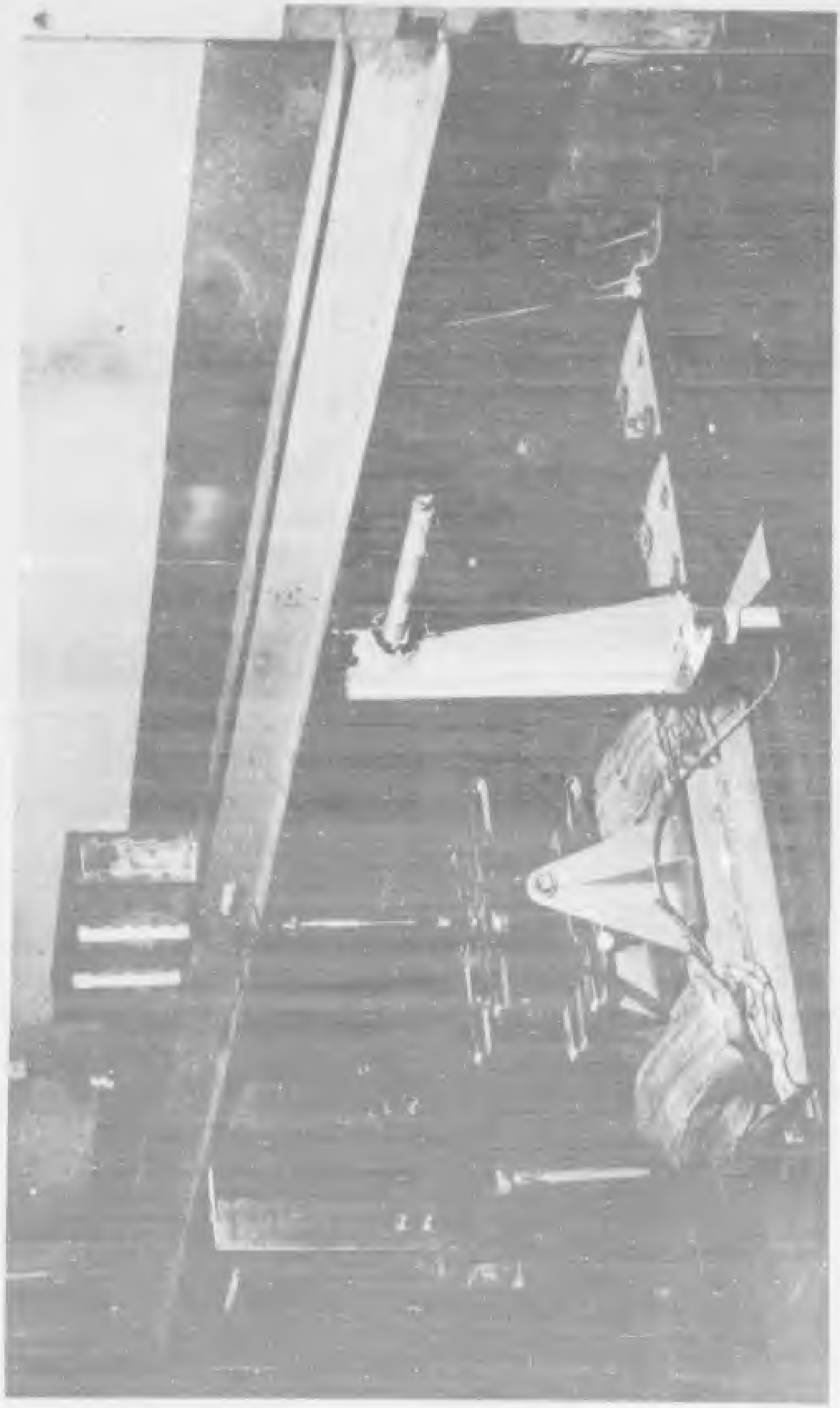


Figure 24. Sand-Damped Beam with Large Box in Horizontal Test Position

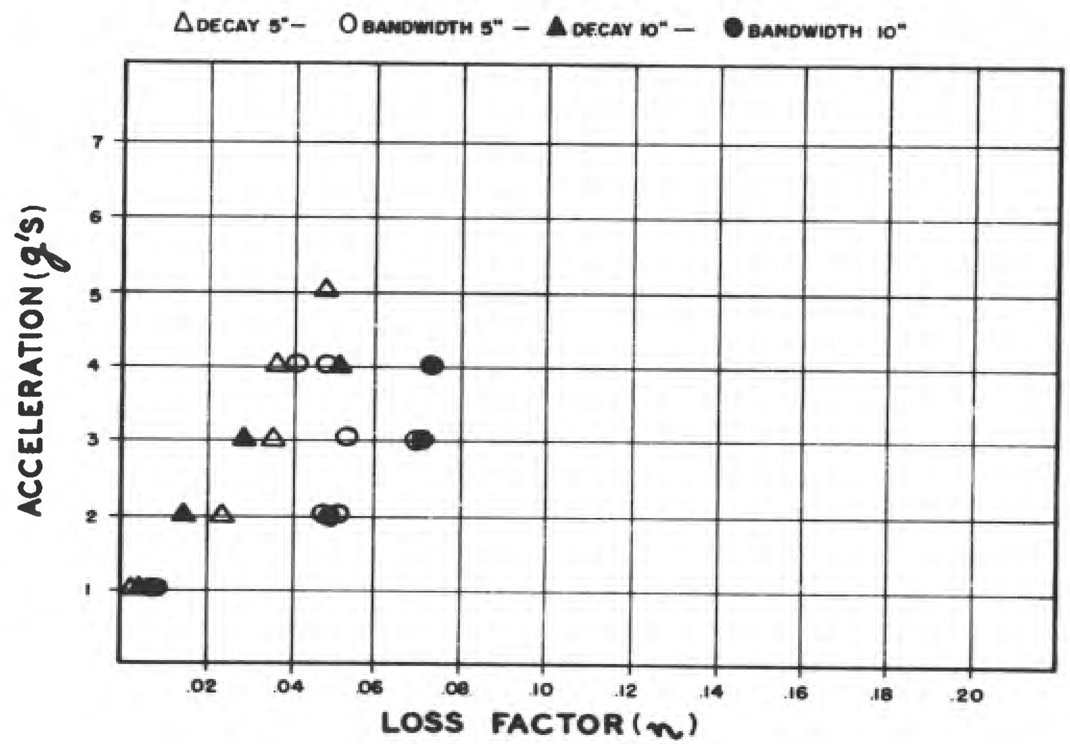


Figure 25. Loss Factor vs. Acceleration for Beam with Large Box; Five and Ten Inches of Pea Gravel; Horizontal Position; First Mode

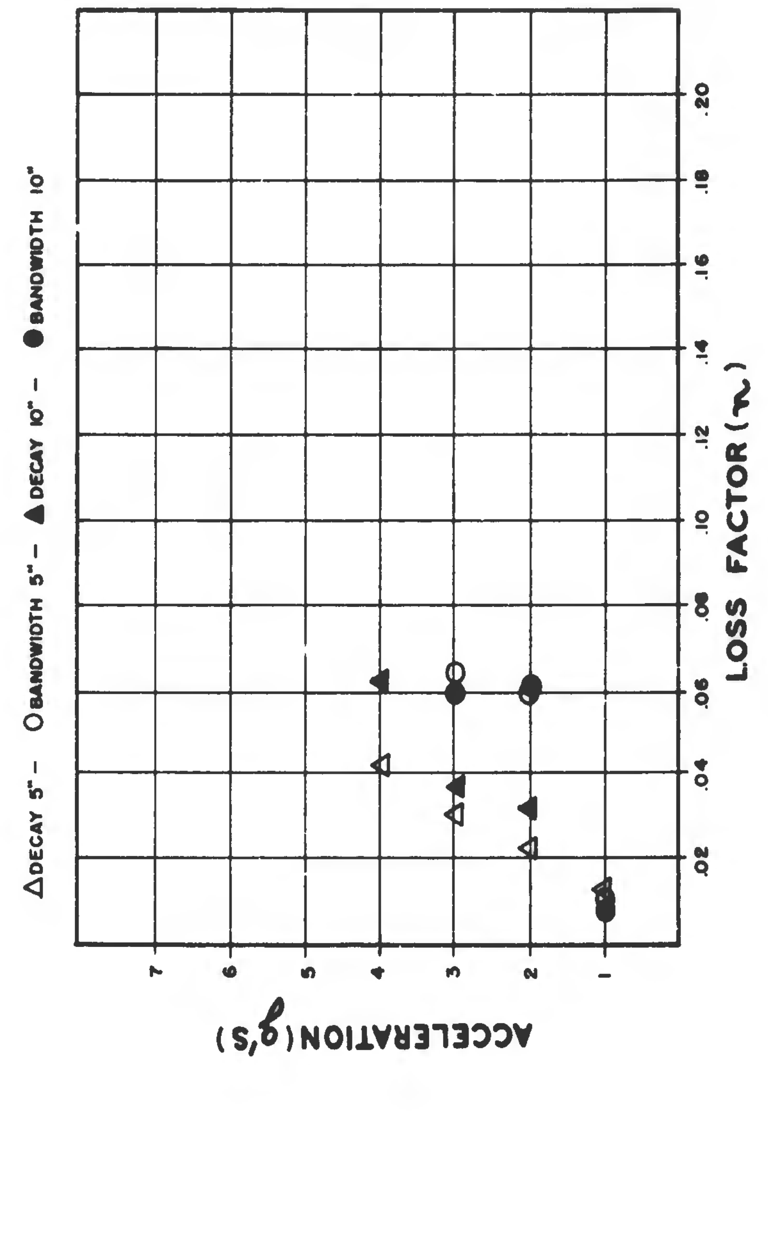


Figure 26. Loss Factor vs. Acceleration for Beam with Large Box; Five and Ten Inches of Washed Mix; Horizontal Position; First Mode

SECTION IV

CONCLUSIONS

Viscoelastic-Damping Tests

Small Beams

1. In general, the measured data points fell below the calculated curve for material A. The 1/8-in.-thick material showed better agreement than did the ¼-in.-thick material (figures 6 and 7). Other points are plotted on the curve to show comparison.

2. The material bonded with cement B gave, in general, the highest values for the loss factor.

3. There appears to have been some variation in the loss factor due to strain dependence of the material but this is difficult to define because of the wide variation in the measured data. In general, the highest loss factors occurred at the highest strain values, but the energy loss to the support member may have been higher at these values of strain. See the data for beam with "no damping."

The data for material C does not compare directly with other data given in figure 6 because of the difference in material thickness.

Large Beams

1. The loss factor as computed by the theory was approximately 10 percent above the measured values, both for the frequency tested and for material A bonded with cement B. See table 2. For cement A, the calculated value was approximately 40 percent above the measured values (table 1).

2. The loss factors computed by the bandwidth method were slightly higher compared to those computed by the decay method.

3. Using two different shakers with the decay technique gave the same loss factors.

4. No variation in the loss factor was found which was due to variation of strain in the viscoelastic material.

5. The loss factors using material A and cement A were substantially below those using cement B.

6. Loss factors measured using material D are not compared to theoretical results because of the lack of materials information.

7. Good agreement existed between values measured by the decay method and the bandwidth method.

8. Loss factors remained constant with varying strain in the material (table 3).

Sandwich-Panel Beam

1. The loss factors as measured by the decay method and the energy method showed no differences. The loss factors measured by the bandwidth method were about 10 percent higher.

2. The loss factors measured with the beam in the horizontal position and the beam in the vertical position showed no differences.

3. The calculated loss factor was about 25 percent higher than the measured loss factors.

4. Bandwidth data taken with the beam oscillating in the second mode showed a tendency toward a split resonance and therefore the data is only approximate. Loss factors here are about 10 percent higher than the calculated values.

5. The loss factors measured in the first case with the viscoelastic material bonded directly to the beam and restraining layer showed little difference compared to the second case in which the sandwich plates were bolted to the beam restraining layer. Compare tables 4 and 5.

Concrete Bars

1. The concrete bars tested with the viscoelastic material bonded directly to the concrete showed that the required damping could be obtained in this manner but after a short test time the bond between concrete and viscoelastic material started to fail around the edges of the material. See table 7 and reference 1.

2. The concrete bars tested with viscoelastic-coated steel reinforcement rods showed that damping could be obtained in this manner but that optimum configurations would have to be determined. See table 8 and reference 1.

Sand-Damping Tests

Concrete Beams and Panel Tests

1. The required magnitude of the loss factors for the full-size panels can be attained with this type of damping.

2. In general, the results showed that the higher loss factors occurred at the higher frequencies and that the damping was strongly dependent upon the acceleration levels. For complete details see reference 1. In some cases, split resonances occurred and loss factors were difficult to measure. In these cases values given are only approximate, and they are marked as such in table 9.

3. Different loss factors were measured for the beam and panel in the horizontal and vertical position.

Steel Beam with Six Boxes

1. In general, it was possible to obtain damping by this method at frequencies as low as 40 cps.

2. The loss factors measured were strongly dependent upon the acceleration levels.

3. Loss factor variations were observed for the same configuration when the beam was tested in the horizontal or vertical position.

4. Loss factor variation occurred at different values of gravel-to-steel weight ratio. The amount of the variation was difficult to define because of the wide scatter in the measured data. The greatest part of the testing was made at the weight ratio of 20 percent because it stimulated the full-scale configuration. The trend of the curve for loss factor vs. acceleration was similar for each weight ratio tested. The loss factor increased sharply with an increase in acceleration.

5. In most cases, different measurement techniques resulted in different values of loss factor for the same configuration and acceleration levels. In certain instances good agreement existed, although no definite trend was established. The data obtained by the decay method was reduced in the same manner as it was when the viscoelastic material was used.

6. Curves showing the loss factor vs. acceleration values for different types of gravel had similar trends in all cases but with variations in the absolute magnitude. Again, the scatter in the measured data was such that no definite conclusion could be made as to which gravel induced the highest loss factor values.

7. Figures 27 and 28 show the formation of the gravel in the six boxes after a shake test.

Steel Beam with One Large Box

1. The conclusions given for the steel beam with six boxes apply equally as well for this case.

2. The loss factors measured with a gravel height of five inches compared to ten inches showed small differences in the measured loss factors. The scatter in the data was such that no definite trend could be established.

3. Figure 29 shows the formation of the gravel in the large box after a shake test.

CONCLUSION SUMMARY

In summary, the tests showed that either the viscoelastic- or the sand-damping method can be applied to large structures satisfactorily.

The merit of the viscoelastic method is that it is based on a well-developed theory from which the amount of damping that can be obtained can be predicted. This, however, depends on whether adequate materials data are available, and, at the present time, this information is available only on some materials. Other pertinent information not available are the loss factor and stiffness data on material that has been in service over a long period of time. Also, the fatigue life of most materials is not known.

The sand damping method offers a cheap way of damping a structure provided the granular substance can be added without increasing the total dead weight of the structure by a large percentage. The temperature independence of the system is an advantage along with its strong non-linear dependency on acceleration. Thus, this method will provide for high damping at the generally more critical stress levels.

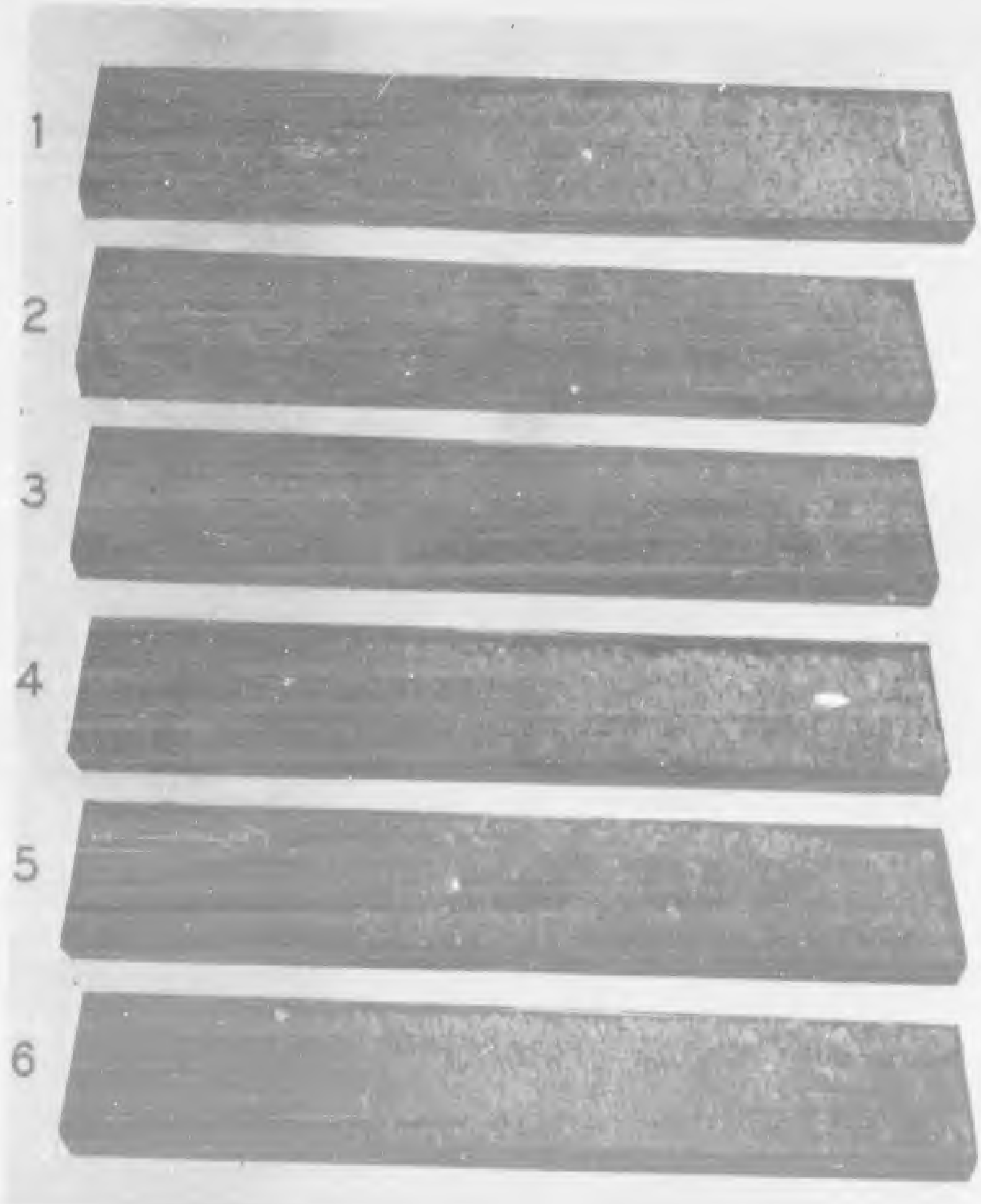


Figure 27. Formation of Crushed Rock and Gravel in Six Boxes After Shake Test

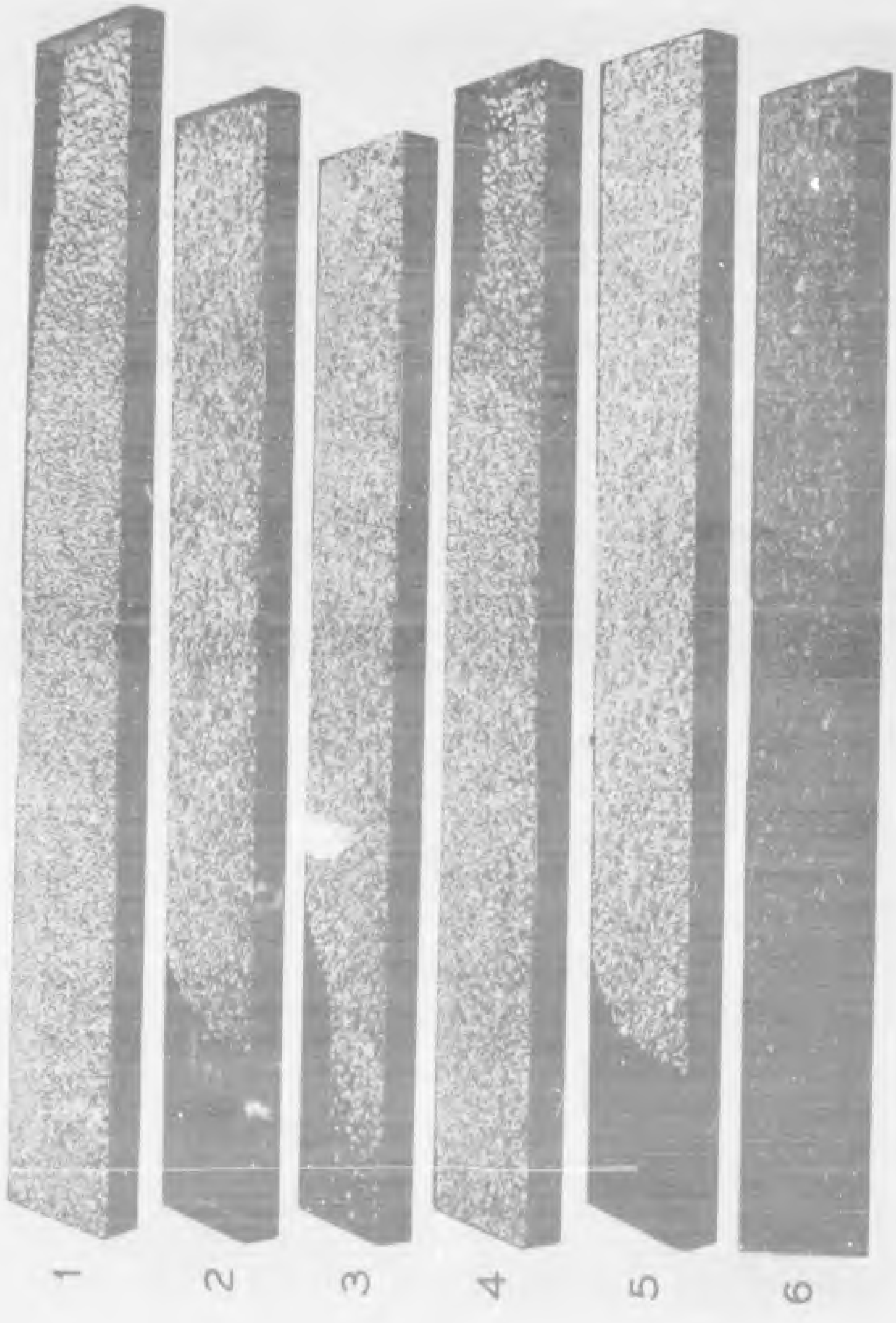


Figure 28. Formation of Washed Mix in Six Boxes After Shake Test

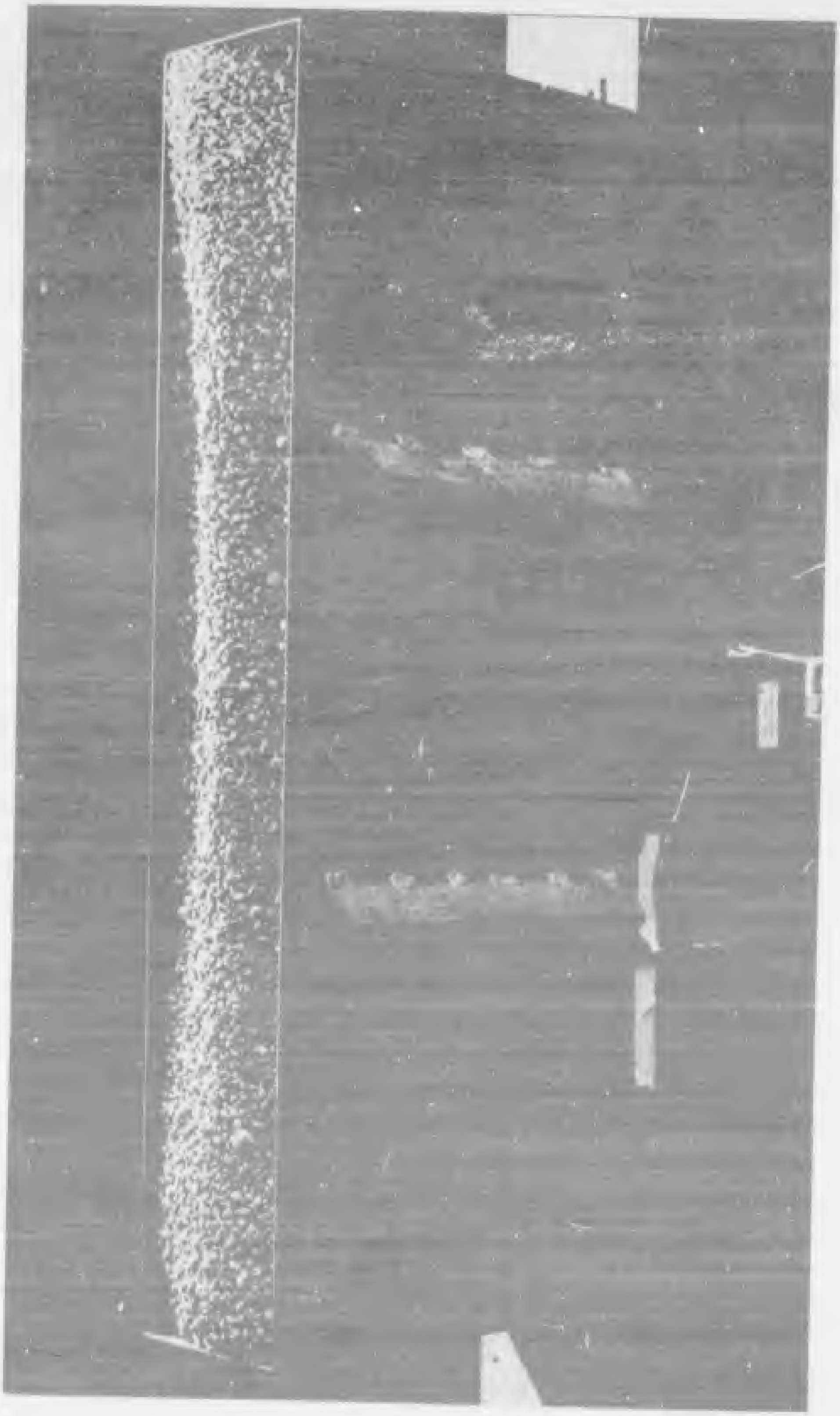


Figure 29. Formation of Pea Gravel in Large Box After Shake Test

APPENDIX

MEASUREMENT TECHNIQUES

A complete review of different techniques and limitations used to measure damping in linear single degree of freedom systems has been discussed in the references (section 5 of ref 1). Some of the equations which were used in making damping calculations and are found in the above mentioned reference are given below:

Decay Method

See figure 30 for nomenclature.

$$\delta = \frac{1}{n} \log_e \frac{x_o}{x_n} \tag{1}$$

$$\eta = \delta/\pi \quad \text{or} \tag{2}$$

$$\eta = \frac{1}{n\pi} \log_e \frac{x_o}{x_n} \tag{3}$$

Bandwidth Method

See figure 31 for nomenclature

$$\eta = \frac{\Delta f}{f_n} \sqrt{\frac{x^2}{x^2_{res} - x^2}} \tag{4}$$

If the bandwidth is measured at the half-power points, or for a 3 db drop, the loss factor is given by

$$\eta = \frac{\Delta f}{f_n}. \tag{5}$$

Energy Method

The loss factor is defined (p. 85 of ref 1) as

$$\eta = \frac{1}{2\pi} \frac{D_o}{W_o} \tag{6}$$

where D_0 is the total damping energy per cycle and W_o is the strain energy in the specimen at the maximum induced stress.

This definition of damping was applied to beam tests performed at ASD to measure damping by energy considerations.

Equation 6 has been applied to a free-free beam in the horizontal position. See figure 32. The beam is supported at A and B. The strain energy W_o is found in the following way.

The general solution for the deflection curve of such a beam is given (p. 331 of ref 5) by the following equation:

$$X = C_1 (\cos kx + \cosh kx) + C_2 (\cos kx - \cosh kx) + C_3 (\sin kx + \sinh kx) + C_4 (\sin kx - \sinh kx) \qquad (7)$$

with the following boundary conditions (p. 336 of ref 5):

1. $\left(\frac{d^2 X}{dx^2}\right)_{x=0} = 0$
2. $\left(\frac{d^3 X}{dx^3}\right)_{x=0} = 0$
3. $\left(\frac{d^2 X}{dx^2}\right)_{x=L} = 0$
4. $\left(\frac{d^3 X}{dx^3}\right)_{x=L} = 0$

With these boundary conditions, equation 7 reduces to the following (p. 336 of ref 5):

$$X = C_1 (\cos kx + \cosh kx) + C_3 (\sin kx + \sinh kx) \qquad (8)$$

If the first mode is assumed (see figure 32 and p. 336 of ref 5)

$$k_2 l = 4.730$$

then equation 8 reduces to (approximately)

$$X = C_3 (-1.018 \cos k_2 x - 1.018 \cosh k_2 x + \sin k_2 x + \sinh k_2 x) \qquad (9)$$

If at $x = L/2$, $X = y_o$, equation 9 reduces to

$$X = y_o/1.32 (\sin k_2 x + \sinh k_2 x - \cos k_2 x - \cosh k_2 x) \qquad (10)$$

The strain energy of bending in the bar is given (p. 297 of ref 6) by

$$W_o = \frac{EI}{2} \int_0^L \left(\frac{d^2 X}{dx^2}\right)^2 dx \qquad (11)$$

Substituting equation (10) into equation (11) gives

$$W_0 = \frac{129\ EI\ y_0^2}{L^3} \tag{12}$$

The total damping energy D_0 was found in the following manner. It is assumed that a sinusoidal force is applied to the beam at M (figure 32).

Then

$$P = P_0 \sin(\omega t + \phi) \text{ and}$$

$$y = y_0 \sin \omega t.$$

If the force and motion have the same frequency the work is given (p. 14 of ref 4) by

$$W = \pi P_0\, y_0 \sin \phi$$

where ϕ is the phase angle between the force and motion (figure 33).

If the system is operated at its first mode resonant frequency, then $\phi = 90°$ and the work per cycle is given (p. 68 of ref 4) by $\pi\ P_0\ y_0$.

The external force is equal and opposite to the damping force so that all the work done in the resonant case is dissipated in damping. Therefore, for the resonant case

$$D_0 = \pi\ P_0\ y_0 \tag{13}$$

By using equations 6, 12, and 13 we obtain

$$\eta = \frac{P_0\ L^3}{129\ EI\ y_0} \tag{14}$$

The natural frequency for such a beam is given (p. 459 of ref 4) by

$$\omega^2 = \frac{(22.4)^2\ EI}{m\,L^3} \tag{15}$$

Substituting equation 15 into 14 gives

$$\eta = \frac{1.95\ P_0}{m\,\omega_n^2\, y_0} \tag{16}$$

Equation 16 gives the loss factor of a free-free beam operating in the first mode at its resonant frequency.

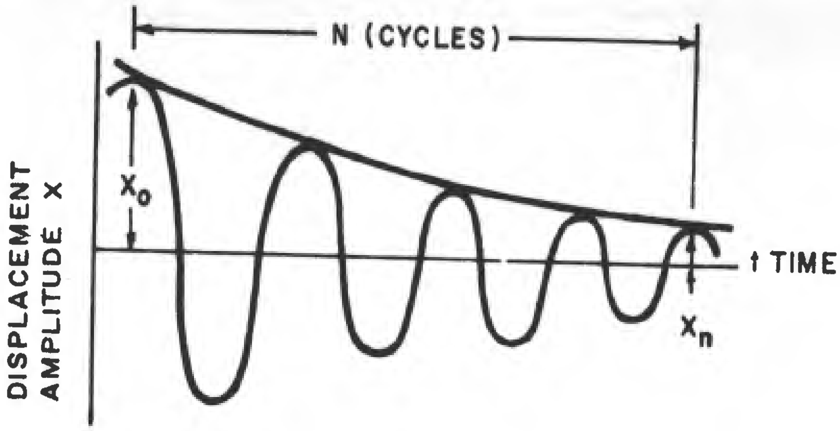


Figure 30. Decay of Damped Vibration

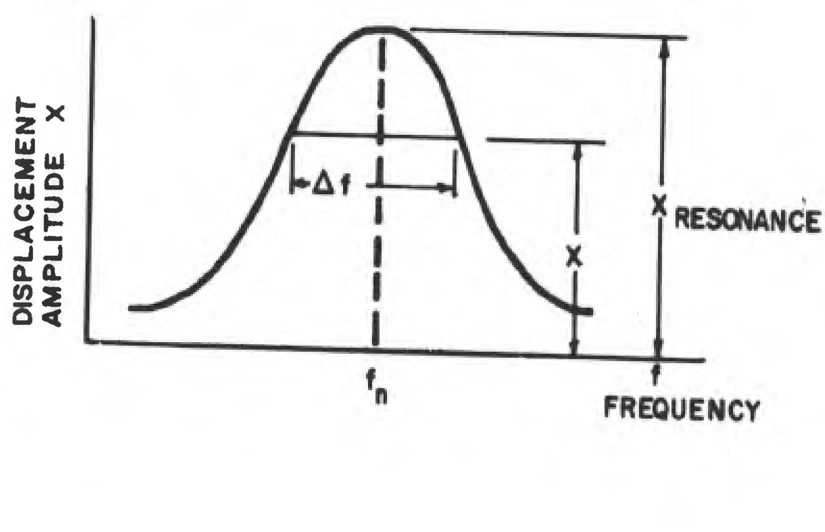


Figure 31. Response Curve

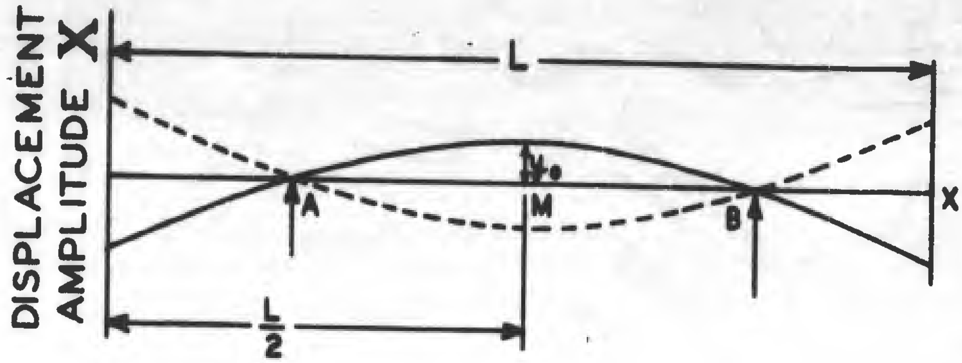


Figure 32. Vibration of Free-Free Beam; First Mode

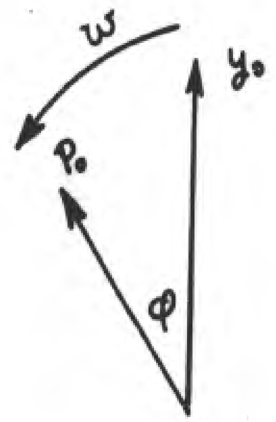


Figure 33. Force Displacement Vector Diagram

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Aeronautical Systems Division, Dir/Engineering Test, Environmental Division, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-62-717. RESULTS OF LOSS FACTOR MEASUREMENTS ON STEEL AND CONCRETE BEAMS USING A VISCOELASTIC OR SAND DAMPING SYSTEM. Final report, Sep 62, 51 pp. incl illus. tables, & 15 refs.

Unclassified Report

The report contains the results of tests to measure loss factors on steel and concrete beams using a viscoelastic or sand damping system. The significance of the tests using the viscoelastic material was the rather large size of the system; for

(over)

the sand damping system, data was obtained at frequencies down to 36 cps. Numerous configurations are tested. For the sand damping case, loss factors are measured as a function of acceleration.

1. Acoustical Damping
2. Structural Damping
3. Mechanical Damping
4. Vibration Mechanisms

I. AFSC Proj 4437
II. Wolf, Nelson D.
III. Not aval fr OTS
IV. In ASTIA collection

Aeronautical Systems Division, Dir/Engineering Test, Environmental Division, Wright-Patterson AFB, Ohio.
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