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A PRELIMINARY INVESTIGATION OF STRAINS AND FRACTURING IN SMALL HYDRO-STONE BEAMS DUE TO IMPACT LOADING

BY

NIELS B. HAUBOLD

A

THESIS

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SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

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Degree of

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1958

Approved -
Assistant Professor of Mining Engineering - Advisor

Approved - George B. Clark
Professor of Mining Engineering, Chairman
Department of Mining Engineering

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Appreciation is expressed to many members of the faculty of the University of Missouri, School of Mines and Metallurgy, for many helpful suggestions. Particular mention is due Mr. R. D. Caudle, Assistant Professor of Mining Engineering, for his valuable aid and advice in the gathering and adapting of the equipment for this investigation; and to Mr. R. F. Bruzewski, Associated Professor of Mining Engineering, for his advice and assistance in the preparation of the pictures contained in this paper.

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INTRODUCTION

Every structure has a fundamental frequency which is sometimes referred to as its first natural frequency. If a periodic force acts on the structure whose frequency is equal to that of the natural frequency of the structure, a vibration is set up whose amplitude would approach infinity if it were not for the presence of damping.[1] Since damping is always present, steady state conditions will finally be reached provided that the applied force is not so great that it will cause the structure to fail. The amplitude of the vibration will be a function of the applied force and the damping capacity of the structure. Steady state conditions will also be finally obtained if a periodic force acts on a structure whose frequency is not equal to the natural frequency of the structure. In this case, the amplitude of the vibration will be a function of the magnitude of the applied force, the damping capacity of the structure, and the ratio of the frequency of the applied force to the natural frequency. The maximum amplitude is obtained when the ratio is equal to 1.

An impulse will excite vibrations also, but no steady state harmonic conditions will be obtained. Either the structure will fail or it will return back to the initial state on account of the presence of damping. The mining engineer is interested in the impact loading of structures, because this is the type of force supplied by the action of explosives.

This is a preliminary investigation of the strain time history in a small hydro-stone beam due to a suddenly applied force. The impact loading was obtained by dropping steel balls from various heights on

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[1] Freberg, C. R., and Kemler, E. N., Elements of Mechanical Vibration, 2d ed., New York, John Wiley & Sons, 1955, p. 56.

the beam. The purpose of the first part of this project was to determine the influence of a number of variables on the strain. The factors which were studied are: a variation in the height of drop and in the weight of the balls; and the effect of the size of the variable resistance wire strain gage on the dynamic strain record. The object of the second part of this project was to investigate the strains present in a small hydrostone beam when it is subjected to an impact loading which is sufficiently large to cause the beam to fail.

EQUIPMENT

The type of equipment used for this investigation and the way in which the various instruments were connected is shown in the form of an over-all block diagram in Figure 1. The outputs of three different circuits were fed into the oscilloscope. The three circuits will be referred to as the strain gage circuit, time calibrator circuit, and the trigger circuit.

STRAIN GAGE CIRCUIT

Variable resistance wire strain gages of the Baldwin bonded type were used for measuring the strain in the beams. A grid of fine wire is the active constituent of this type of gage. After the gage has been cemented to a surface, any strain in the same will deform the fine wire of the gage, and thus change its resistance. Within limits the change in resistance of the gage is proportional to the strain in the structure.[2]

A Du Mont Type 335 Strain Gage Control was used to measure the change in resistance of the gage. A Wheatstone bridge circuit and means by which the bridge circuit can be balanced are incorporated within the instrument. Thus it was possible to obtain a zero output voltage with unstressed gages. In addition, the strain Gage Control provided supply voltages and a circuitry for the calibration of the variable resistance wire strain gages. A schematic diagram of the type of circuit used for this investigation is shown in Figure 2.

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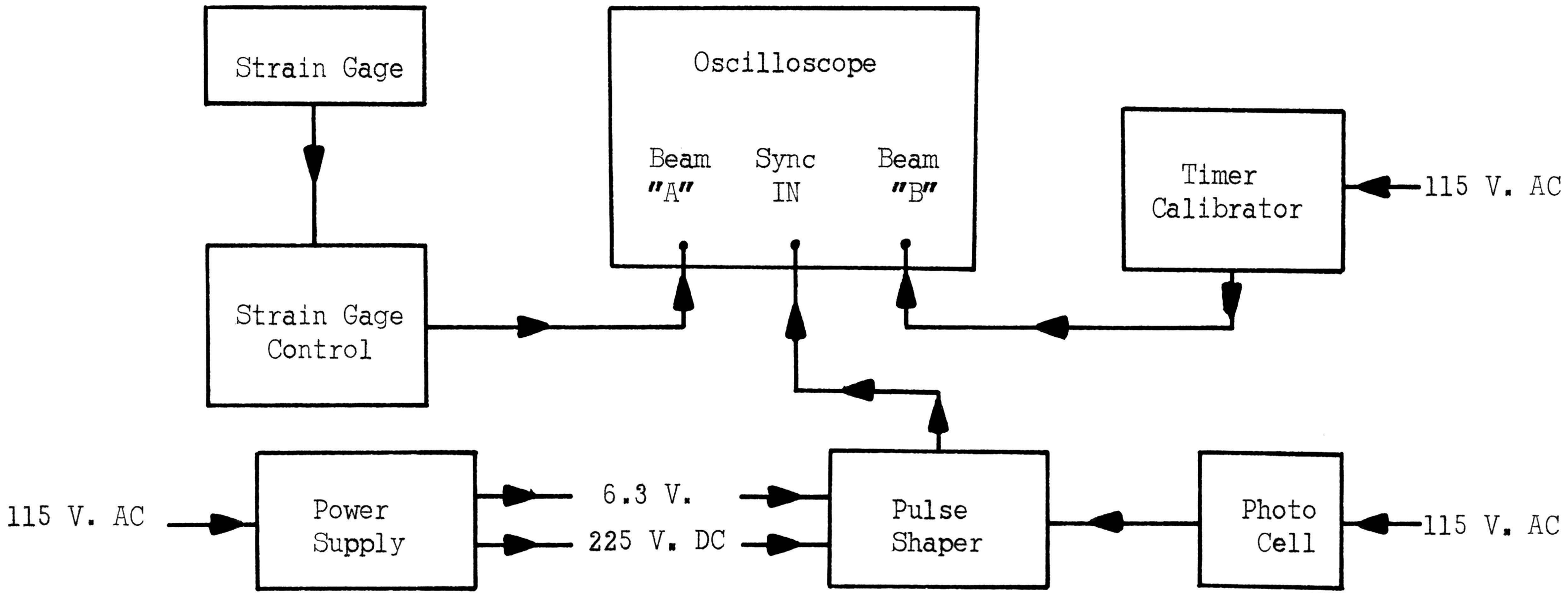
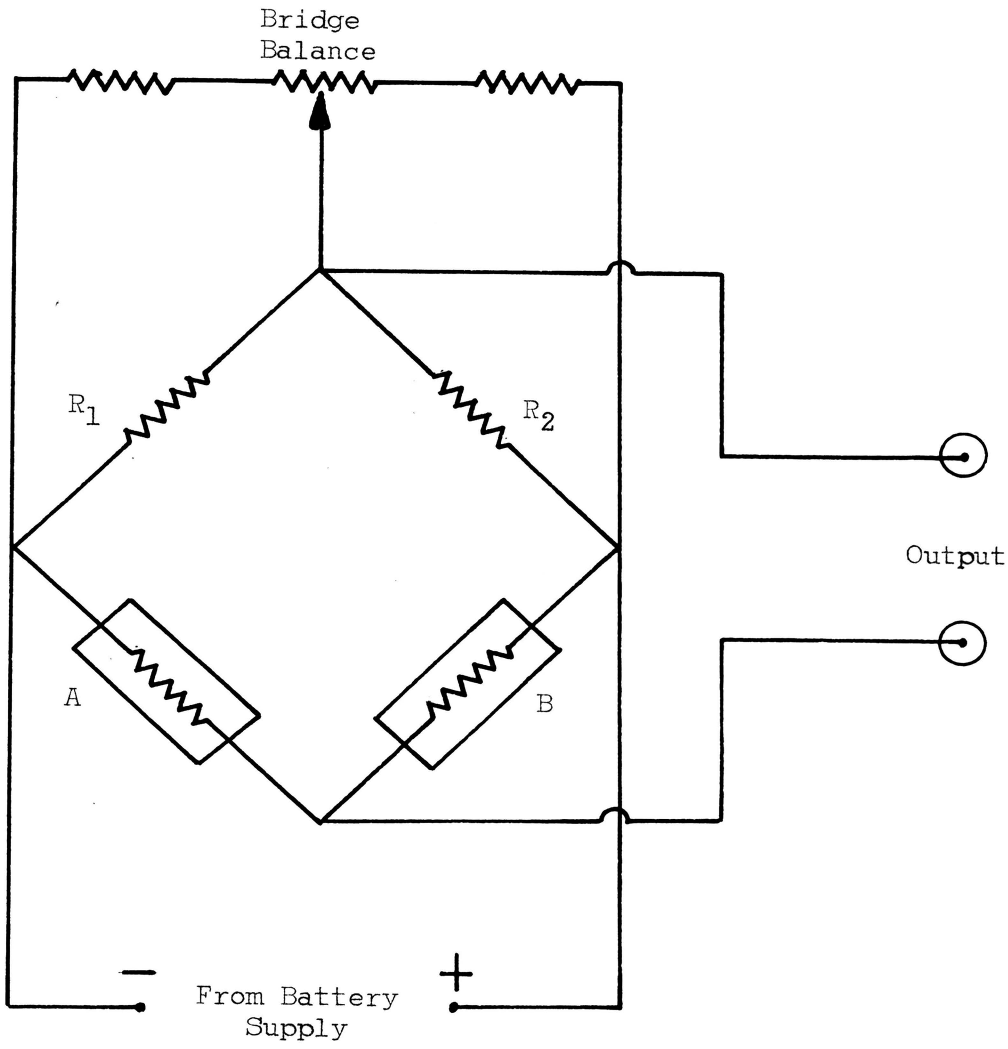
[2] Lee, G. H., An Introduction to Experimental Stress Analysis, New York, John Wiley & Sons, 1950, pp. 113 - 117.



Description of Equipment

Time Calibrator:	Du Mont Type 300 Time Calibrator
Oscilloscope:	Du Mont Type 333 Dual Beam Cathode-Ray Oscillograph
Strain Gage:	Variable resistance wire strain gage of the Baldwin bonded type
Gage Control:	Du Mont Type 335 Strain Gage Control
Pulse Shaper:	Built in laboratory after circuit in Du Mont Type 300 Time Calibrator
Power Supply:	Heathkit Variable Voltage Regulated Power Supply, Model PS-3.
Photo-Cell:	Allied Radio Corporation Knight-Kit Photoelectronic Relay modified as shown in Figure 3

Figure 1. Over-all block diagram of equipment



Note:

R_1 and R_2 are equal precision resistors

A is the active gage

B is the temperature-compensating gage

Figure 2. Schematic diagram of strain gage circuit

Strain gages were used for the resistances of two opposite arms of the Wheatstone bridge. One gage was the active or strain-measuring gage and the other was the temperature-compensating gage.[3] The output of the strain Gage Control was fed into the "A" beam of a Du Mont Type 333 Dual Beam Cathode-Ray Oscillograph. The strain indications were recorded photographically with a Du Mont Type 296 Oscillograph Record Camera.

TIME CALIBRATOR CIRCUIT

A Du Mont Type 300 Time Calibrator was used for the superposition of timing markers on the trace of the "B" beam of the dual beam oscilloscope.

TRIGGER CIRCUIT

An additional circuit was necessary for triggering a single sweep on the oscilloscope at the instant when the ball struck the beam. The output of an Allied Radio Corporation Knight-Kit Photoelectronic Relay was fed into the external synchronizing terminals of the oscilloscope. The relay was activated when the falling ball interrupted a beam of light. The inadequacy of this circuit became evident during the first trial runs.

A suitable circuit was designed after considerable experimentation. The circuitry of the Allied Radio Corporation Knight-Kit Photoelectronic Relay was revised so that an output signal of a rapid voltage rise was obtained when the light beam was broken. The first interruption of the light beam provided the synchronizing pulse. No output was obtained from any further interruptions unless the circuit had previously been

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[3] Lee, G. H., op. cit., p. 120.

manually reset. The delay time of the instrument was made constant by replacing the a.c. voltage supply for the thyraton by a d.c. supply. The circuit diagram of the photo-cell used for initiating the impulse is shown in Figure 3.

The output of the photo-cell was fed into a pulse shaper which was built for this investigation. This was necessary in order to reduce the rise time of the pulse so that only one sweep would be obtained on the fluorescent screen of the oscilloscope. The circuit of the pulse shaper is identical to the one found in the Du Mont Type 300 Time Calibrator. The operation of the pulse shaper is based on the Schmitt-trigger principle. The 6.3 volts alternating current and the 225 volts direct current required for the operation of the pulse shaper were supplied by a Heathkit Variable Voltage Regulated Power Supply, Model PS-3.

MISCELLANEOUS EQUIPMENT

A coil connected to a 6 volt battery served as an electro magnet. The steel balls were released from the magnet by throwing a switch which opened the circuit. The beam to be tested was supported on the edges of two triangular shaped steel prisms which in turn were attached to a large steel block. A Heathkit Decade Resistance, Model DR-1, in series with a sufficiently large precision resistor was used for calibrating the strain gages. An additional Wheatstone bridge with a circuit diagram as is shown in Figure 2 was built so that the strains measured by two gages could be recorded simultaneously, if desired. The voltage supply for the bridge circuit was obtained from batteries.

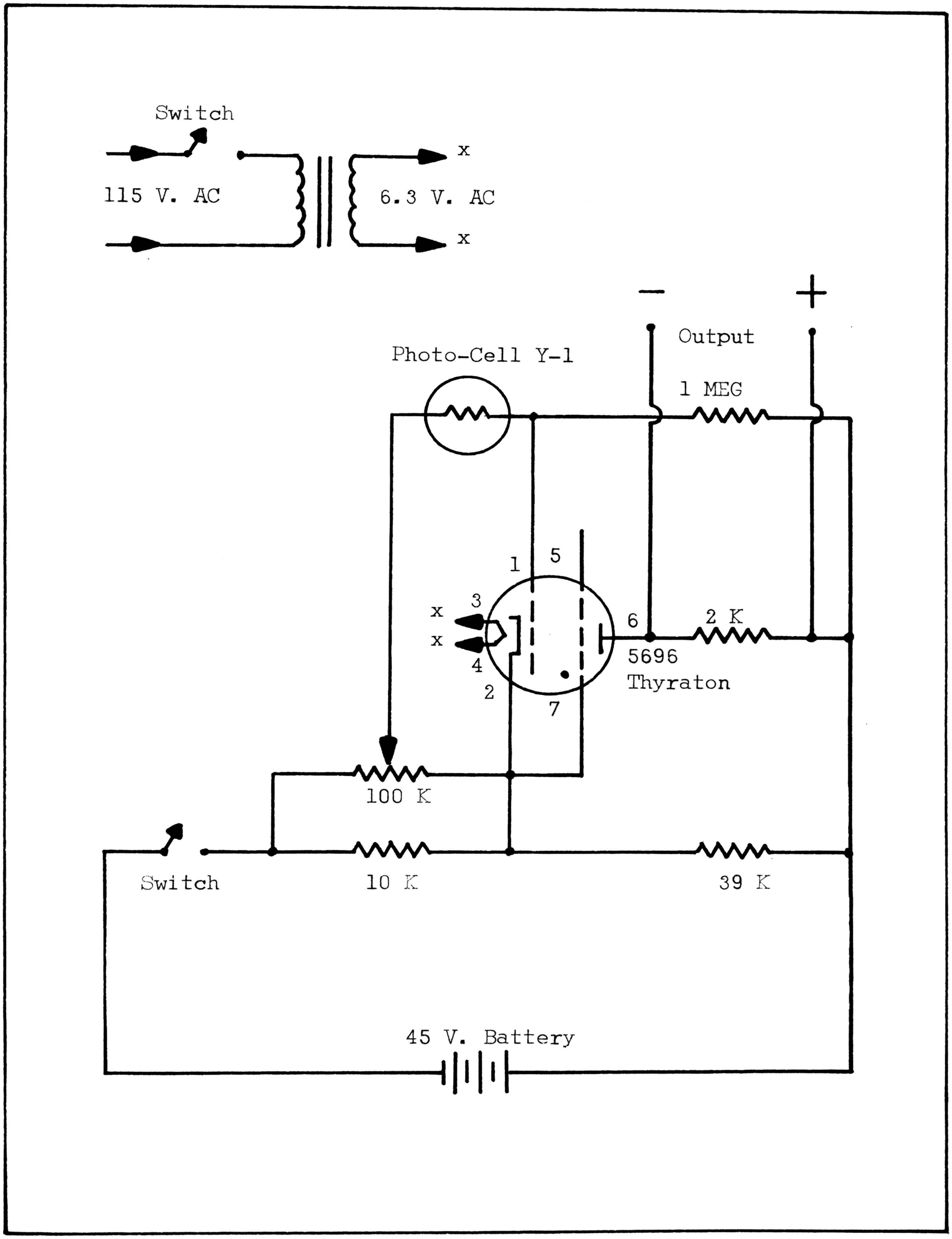

Figure 3. Photo-cell circuit diagram

TEST PROCEDURE

A period of approximately 30 minutes was allowed for the instruments to warm up before any testing was done. Then they were checked to obtain proper adjustment. Special care was given the y-axis multiplier balance of the oscilloscope, because different voltage amplification scales were used during the tests.

The Wheatstone bridge circuit was balanced with unstressed gages by adjusting the potentiometer on the strain Gage Control. The calibration of the strain gage was the next step in the test procedure. This was done by shunting a known resistor across the strain gage which reduced the effective resistance of the strain gage by a given amount. The same unbalance of the bridge circuit may be obtained by a certain compressive strain in the structure. The following equation gives the relationship between the strain and the calibrating resistor:[4]

$$e = \frac{R_a}{(GF)\ (R_a - R_c)}$$

in which:

R_a = resistance of active gage in ohms.

R_c = resistance of calibration resistor in ohms.

e = strain in inches per inc.

GF = gage factor.

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[4] Lee, G. H., op. cit., p. 136.

The equation was solved for the calibration resistance in terms of the other variables, as is shown:

$$R_c = \frac{Ra\ (1 - e \cdot GF)}{e \cdot GF}$$

Thus one was able to obtain a given strain equal to a deflection of one major division on the oscilloscope at a specific voltage amplification scale. A few trial runs were carried out next to determine if a proper deflection was obtained on the screen and if the photo-cell was at such a height that the initial strain was being recorded on the sweep. The deflection for a given strain may be varied by using a different calibration resistance or by changing to a different amplification scale on the oscilloscope. The height of the photo-cell was adjusted by trial and error until the initial point on the strain-time curve appeared on the screen.

The sweep rate was adjusted by trial and error until satisfactory pictures were obtained. Timing markers at an interval of 100 micro seconds were used for all tests. The camera was then attached to the oscilloscope and the equipment was ready for the investigation. Tri-X film was used exclusively. The diaphragm opening was set at f/2.8 and the shutter at "Bulb." A picture of the grid on the fluorescent screen was obtained with an exposure time of approximately five seconds, due to light from the filament of the cathode-ray tube.

TESTS

The variables which were taken into consideration in the investigation were as follows:

1) weight of the balls
2) height from which balls are dropped
3) type of strain gage used

Other variables which could be investigated in future work, but were held constant during any one of these tests are:

1) the dimensions of the beam
2) spacing between supports
3) boundary conditions
4) point at which load is applied

The length of all beams tested was equal to 12¼ inches and their width was equal to 2 3/4 inches. There was a variation in the thicknesses of the beams. Therefore, the thicknesses of the beams were held constant only for a particular series of tests. The distance between supports was held constant at 10½ inches.

The beams were tied down to the supports with rubber bands. This gave boundary conditions which resemble those of a simple supported beam closely, because there will be little, if any, moment and displacement at the supports. The first pictures showed that great variations in results would be obtained, if the balls were not dropped exactly on the geometric center of the beams. During all the following tests, the geometric center of the beam was marked and great care was taken so that the ball would strike the beam at that point.

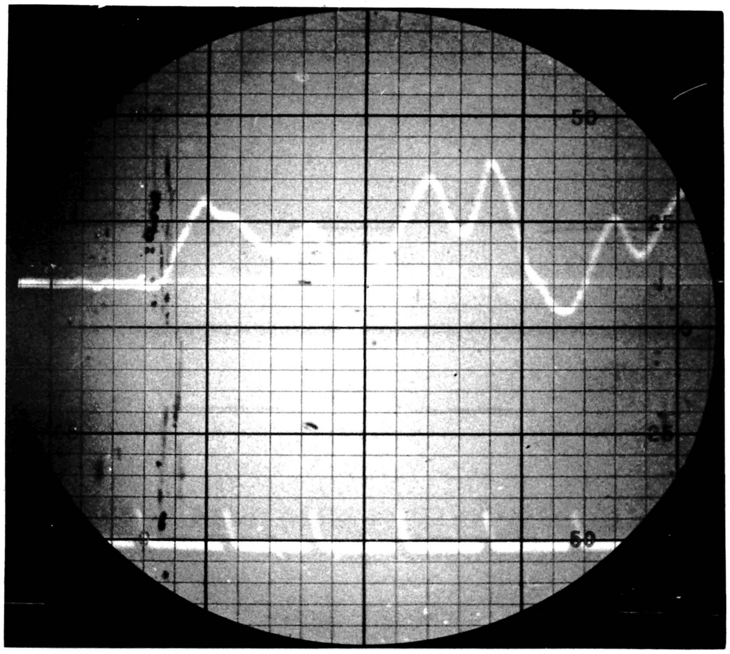
TESTS WITH BALLS OF VARIOUS WEIGHTS

In the first part of the investigation all the variables were held constant but the weight of the balls. Records of these tests are shown in Figure 4 and Figure 5. From these pictures and others which were studied it was possible to determine a qualitative relationship between the weight of the ball used and the magnitude of the strain obtained. The length of time required for the strain to reach its first peak and its maximum value; and also the corresponding magnitudes of strain are given in Table 1 for a series of tests on a beam.

Table 1. Results of tests with balls of various weights. Measurements are given of time intervals required for the strain to reach its first peak and its maximum value; and also the corresponding magnitudes of strain. The balls were dropped from a height of $42\frac{1}{2}$ inches on a 0.88 inch thick hydro-stone beam. A Baldwin type C-8 gage was used.

Weight of ball oz	Time to 1st peak 10^{-6} sec	Strain at 1st peak 10^{-6} in/in	Time to max strain 10^{-6} sec	Max strain 10^{-6} in/in
0.41 *)	53	126	387	186
0.59	50	160	379	232
0.77	70	206	399	274
0.88	63	242	388	336
1.58 **)	66	410	387	568

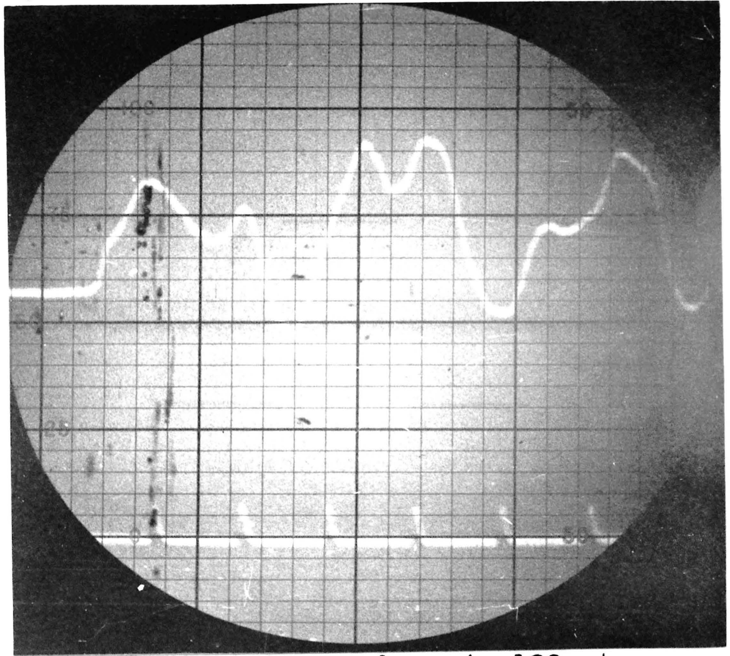
*) Dynamic strain record shown in Figure 4.
**) Dynamic strain record shown in Figure 5.



One major division is equal to
160 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 4. Dynamic strain record obtained with a Baldwin type C-8 strain gage by dropping a 0.41 oz. steel ball on a 0.88 inch thick hydro-stone beam from a height of 42½ inches (Drop No. 6-12-OA).



One major division is equal to
400 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 5. Dynamic strain record obtained with a Baldwin type C-8 strain gage by dropping a 1.58 oz. steel ball on a 0.88 inch thick beam from a height of 42½ inches (Drop No. 6-12-5A).

The values of Table 1 show that there is a considerable increase in the strain within a beam as the weight dropped on it becomes larger. There was no apparent relationship between the weight of the ball dropped and the time interval from the time of impact until the strain reaches any particular point on the strain-time curve.

The oscillatory motion which made it difficult to obtain quantitative values for the rate of strain was investigated next. The assumption was made that the motion is of a harmonic form. The equation for the natural frequencies of a uniform beam simply supported at the ends is:[5]

$$f = \frac{n^2 \cdot \pi}{2} \cdot \sqrt{\frac{g \cdot E \cdot I}{w \cdot L^4}} = C \cdot \sqrt{\frac{g \cdot E \cdot I}{w \cdot L^4}} \text{ cycles/sec}$$

$$C = \frac{n^2 \cdot \pi}{2} = \frac{\pi}{2}, \frac{4 \cdot \pi}{2}, \frac{9 \cdot \pi}{2}, \text{ etc.}$$

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[5] Freberg, C. R., and Kemler, E. N., op. cit., p. 140.

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in which :

g = acceleration of gravity in inches per second square

E = modulus of elasticity in pounds per square inch

I = moment of inertia of beam section in inches to the fourth power

w = beam weight in pounds per inch

L = beam length in inches

n = mode of vibration

For the beam tested:

$g = 386$ in/sec^2

$E = 2.5 \cdot 10^6$ lbs/in^2

$I = 0.154$ in^4

$w = 0.151$ lbs/in

$L = 12\frac{1}{2}$ inches

The equation for its natural frequencies becomes:

$$f = 284 \cdot C \text{ cycles/sec}$$

The periods of the various harmonic frequencies were determined theoretically so that they could be compared with the periods of the vibrations on the strain records. The period is equal to the inverse of the frequency. The results of the calculations are shown in Table 2.

Table 2. Periods of the fundamental frequency and of higher harmonics of a simply supported hydro-stone beam - the dimensions are 0.88 by 2.75 by 10.50 inches.

Frequency	Period in micro seconds	n
Fundamental	2240	1
First harmonic	560	2
Second harmonic	250	3
Third harmonic	140	4

When the calculated periods were compared with the wave motion on the pictures, it could be seen that the second harmonic frequency was the most prominent one. This vibration is superimposed on the fundamental mode. The dynamic strain record shown in Figure 6 gives a good representation of this relationship. A number of higher frequency vibrations have to be present in addition to the fundamental frequency and the second harmonic to account for the distortion of the second harmonic which can be seen on all dynamic strain records.

These vibrations are caused by the same type of loading and the same boundary conditions as the fundamental and the second harmonic vibrations. Higher harmonics which will satisfy these conditions are the sixth, tenth, and fourteenth harmonic frequencies. No attempt was made during this investigation to identify any vibrations whose frequency is greater than that of the second harmonic.

TESTS WITH DROPS FROM VARIOUS HEIGHTS

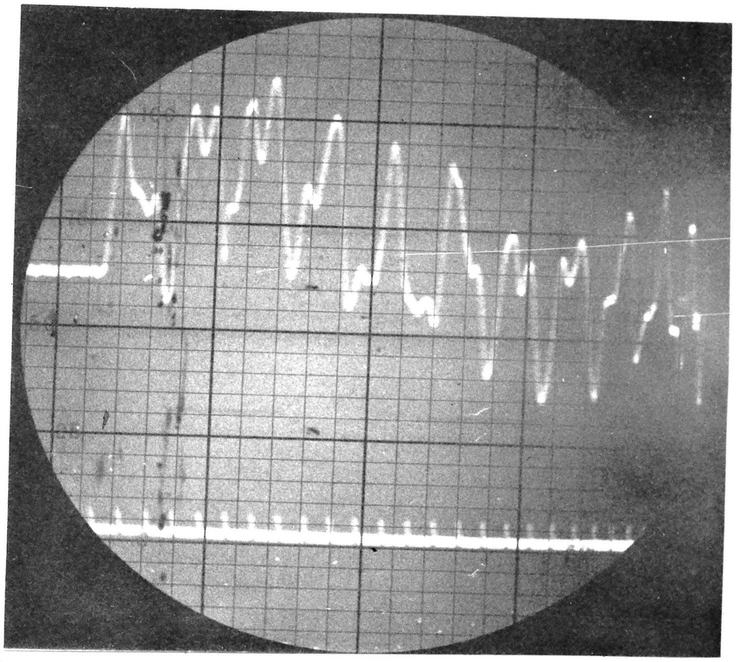
In the second part of the investigation all the variables were held constant but the height from which the ball was dropped.

Table 3. Results of tests with dropping a ball from various heights. Measurements are given of the time interval required for the strain to reach its first peak and the corresponding magnitude of strain. A 0.77 oz steel ball was dropped on a 0.98 inch thick beam. A Baldwin type C-5-1 gage was used.

Height of drop in	Time to 1st peak 10^{-6} sec	Strain at 1st peak 10^{-6} in/in
8.1 *)	67	117
13.8	57	170
18.2	61	175
29.5	56	205
35.4	44	258
41.4	44	284
46.9 **)	46	300

*) Dynamic strain record shown in Figure 6.
**) Dynamic strain record shown in Figure 7.

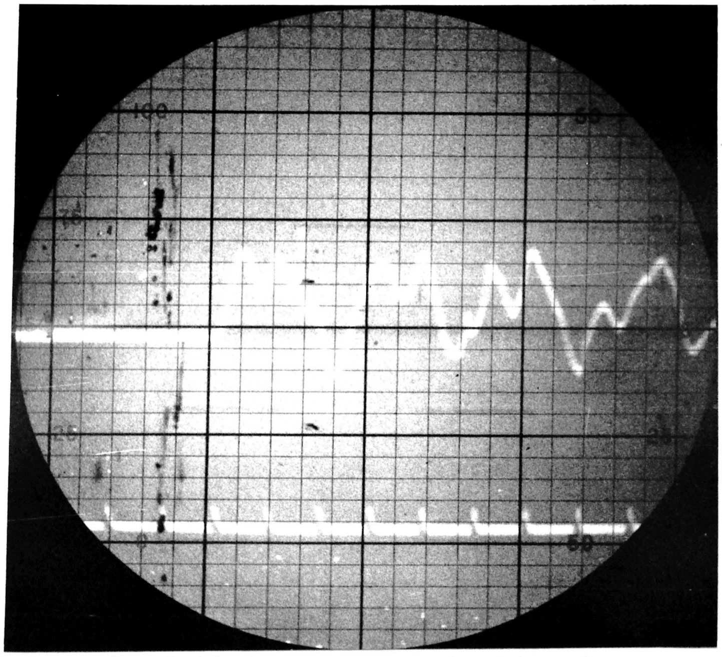
Note: Weight of balls was varied by selecting steel balls with different diameters. The effect of different radius of curvature was included as part of the weight parameter.



One major division is equal to 80 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 6. Dynamic strain record obtained by dropping a 0.77 oz steel ball on a 1.00 inch thick beam from a height of 8.1 inches. Baldwin type C-5-1 gage was used for measuring strain (Drop No. 6-19-12B).



One major division is equal to 400 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 7. Dynamic strain record obtained by dropping a 0.77 oz steel ball on a 1.00 inch thick beam from a height of 46.9 inches. Baldwin type C-5-1 gage was used for measuring strain (Drop No. 6-19-15C).

A 0.77 oz steel ball was dropped and Baldwin type C-5-1 variable resistance wire strain gages were used to measure the strain. The results for a series of tests on a 1.00 inch beam are shown in Table 3. The dynamic strain records obtained by dropping a 0.77 oz steel ball from a height of 8.1 inches is shown in Figure 6 and from a height of 46.9 inches in Figure 7.

The results obtained from tests with dropping the same ball from various heights are similar to those obtained in the first part of the investigation. The same harmonic vibrations are present. One can see by comparing Figure 6 and Figure 7 that balls dropped from greater heights excite the higher harmonics to a greater extent. This can be seen especially well for the fundamental wave, which is obscured.

TESTS WITH DIFFERENT SIZES OF STRAIN GAGES

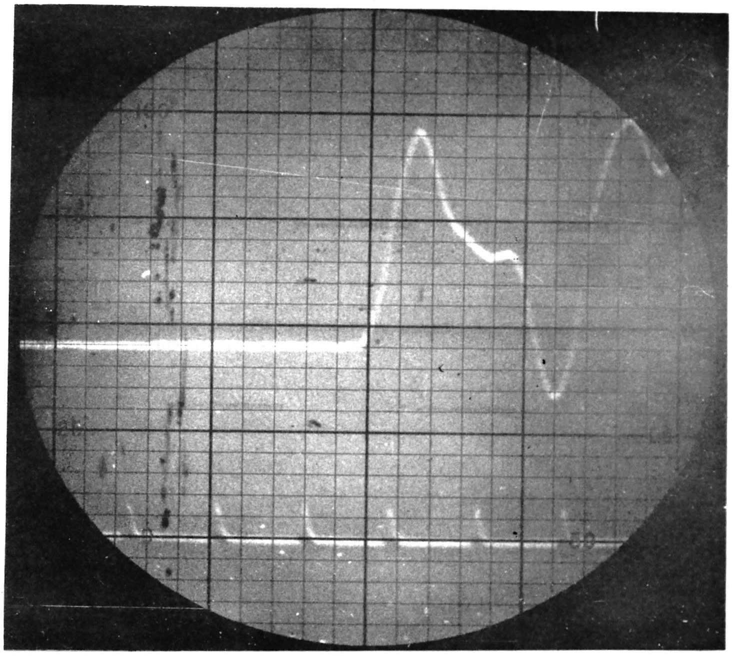
Tests were carried out in which all the variables were held constant but the size of gages used. A 1.58 oz steel ball was dropped from a height of 42.2 inches on 1.0 inch beams. Table 4 gives the results of a typical test run. The dynamic strain record obtained with a Baldwin type C-8 variable resistance wire strain gage is shown in Figure 8 and with a Baldwin type A-3 gage is shown in Figure 9.

The results of this test demonstrate that the size of the variable resistance wire strain gage used has an influence on the magnitude of the recorded dynamic strains. The Baldwin type A-3 gage recorded a smaller strain than the other types of gages used, which were shorter in length. There was no apparent difference in the dynamic strain records obtained with the Baldwin type C-5-1 and C-8 gages. An attempt will be made to

Table 4. Measurements of strains with different sizes of gages. The strain was obtained by the impact loading of a 1.0 inch beam by a 1.58 oz steel ball released from a height of 42.2 inches.

Type of Baldwin gage	Length of active element in inches	Strain at 1st peak in micro in/in
C-8	0.12	408
C-5-1	0.44	410
A-3	0.80	350

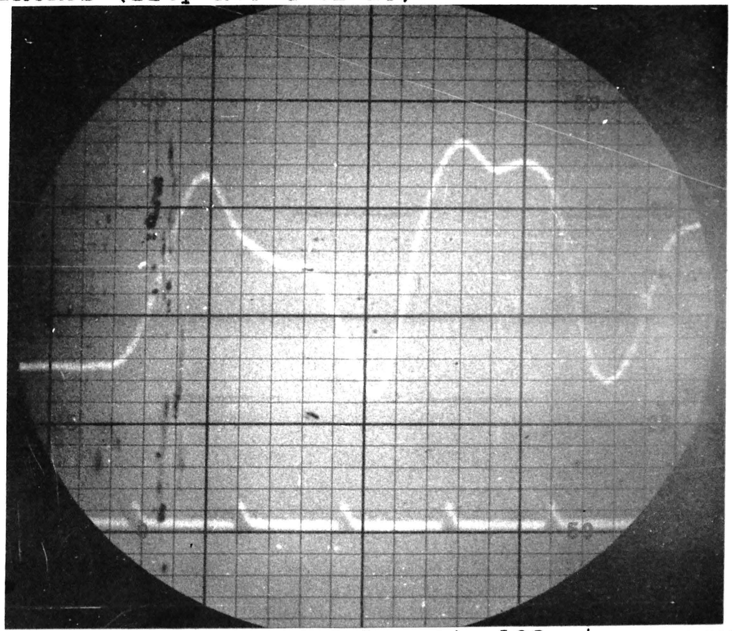
explain the similarity in readings obtained with the two gages, although there is a considerable difference in their lengths. The vibrations within a beam will cause a maximum deflection at some instant at the point where the particular gage is attached. To either side of this maximum point, the values of strains would be somewhat smaller. Since the strain recorded by a variable resistance wire strain gage is proportional to the change in the length of the gage to its original length, the measurement obtained from the gage will be the average strain over its total length. Therefore, the shorter the gage is the greater should be the recorded strain, since the maximum strain is always located at a point along the beam at any instant; and the error in recording the strain will become increasingly greater as the length of the gage becomes larger. The Baldwin type C-5-1 gage was small enough to give sufficiently accurate readings, as indicated by the agreement with the smaller C-8 gage reading.



One major division is equal to 200 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 8. Dynamic strain record obtained with a Baldwin type C-8 variable resistance wire strain gage. The record was obtained by the impact loading of a 1.0 inch beam with a 1.58 oz steel ball released from a height of 42.2 inches (Drop No. 6-12-13).



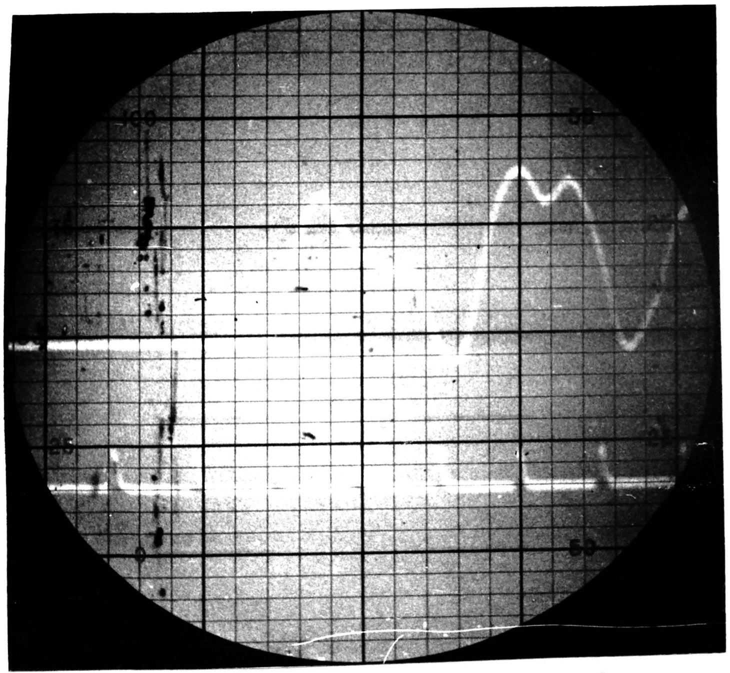
One major division is equal to 200 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 9. Same dynamic strain record as in Figure 8 but obtained with a Baldwin type A-3 variable resistance wire strain gage (Drop No. 6-19-11A).

FAILURES OF BEAMS

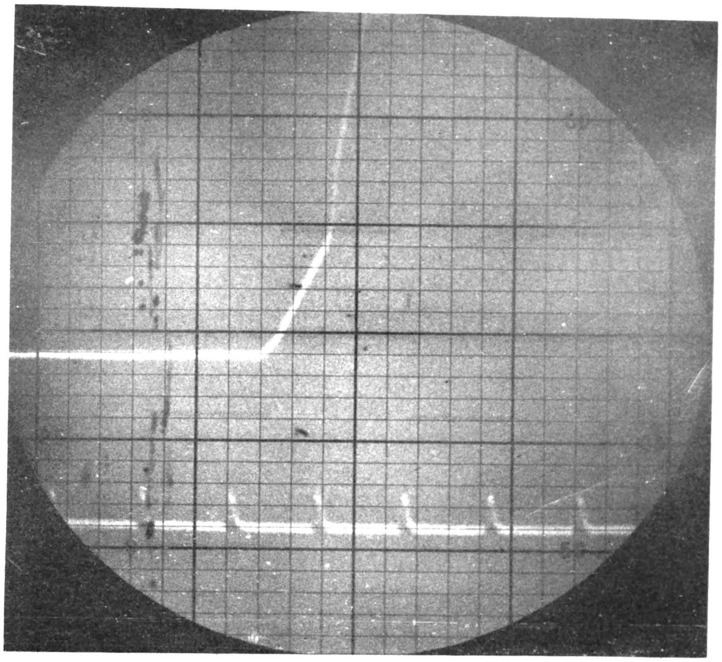
In this part of the investigation, an attempt was made to determine what takes place within a beam when it is subjected to an impact load which is large enough to cause the beam to fail. A record of such a loading is shown in Figure 10. This picture was obtained by increasing the weight of the balls gradually until one finally caused the beam to fail. The beam broke through its center and thus at the place where the strain gage was attached. As can be seen from the dynamic strain record, the beam did not fail at the first or second peak of maximum strain. One may conclude that the time at which failure will take place is dependent on the superposition of all the harmonic frequencies present when the impact load is just sufficiently large to break the beam.



One major division is equal to 400 micro in/in of strain

Interval of timing markers is 100 micro seconds

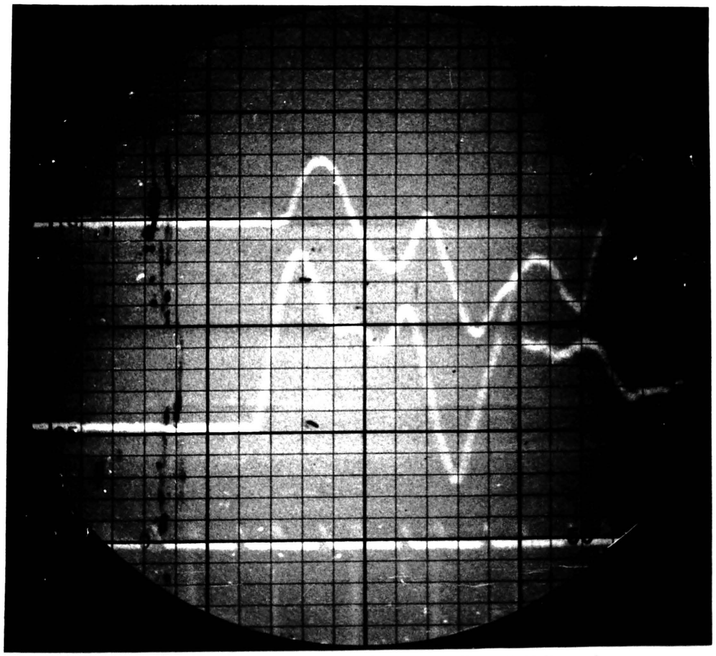
Figure 10. Dynamic strain record obtained with an impact loading just large enough to cause the beam to fail (Drop No. 6-4-8).



One major division is equal to 500 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 11. Dynamic strain record obtained with an impact loading considerably in excess of the minimum required to cause the beam to fail (Drop No. 6-12-4B).



One major division is equal to 400 micro in/in of strain

Interval of timing markers is 100 micro seconds

Figure 12. Dynamic strain record of the failure of a beam. The lower curve was obtained with a strain gage mounted at the geometric center of the beam. The upper curve was obtained with a gage mounted 2 inches from the other along the axis of the beam. (Drop No. 6-13-11).

The combination of all the harmonic vibrations present may cause the maximum strain to occur at the second, third, or a later peak in spite of damping which is always present and which could lead to the erroneous conclusion that the maximum strain will occur at the first peak.

The type of failure obtained due to a loading which is considerably greater than the minimum necessary to break the beam is shown in Figure 11. The fracture went through the center of the beam and through the gage as can be seen from the record. One may conclude from this test that the beam will fail at, or before, the strain reaches its first peak, if the impact load is sufficiently large.

The strains in the remaining parts of the beam immediately after failure were also investigated. A test was carried out in which two Baldwin type C-7 variable resistance wire strain gages were attached to a beam. One strain gage was cemented to the geometric center of the beam and the other one two inches from the first one along the axis of the beam. A dynamic strain record of the failure of the beam is shown in Figure 12. The fracture missed the strain gage at the center of the beam by 0.2 inches and the other strain gage by 2.2 inches. One may conclude from this picture that an immediate strain relief takes place in the close vicinity of the fracture only. The vibrations at a distance from the fracture are not affected. This explains the possibility of a beam failing at more than one place. This happened to a number of beams which were broken.

CONCLUSIONS

Impact loading of hydro-stone beams will excite harmonic vibrations the instant at which the load is being applied. The effect of a change in weight of the balls and of a change in the height from which they were dropped on the resulting harmonic vibrations was investigated. Similar results were obtained in both tests. An increase in the magnitude of the strain is recorded if the height is increased and if the weight of the ball is increased. On the other hand, it was not possible to obtain any relationship between the time it takes for the strain to reach the first peak, or any other point, on the strain-time curves and the height or the weight of the balls used. Since the magnitude of the strain increases and the time interval changes only a small amount, if at all, one may conclude that the time rate of strain within a beam increases with an increase in the height of drop and in the weight of the ball used.

This investigation furnished qualitative results only. Therefore, the type of variable resistance wire strain gage used was not too significant, because they all indicated the vibrations present. The length of the strain gage used has an influence on the magnitude of the recorded dynamic strains and should be given consideration if one is interested in obtaining quantitative values. The results of this investigation show that long gages will record smaller readings for the same strains than short gages. On the basis of this investigation one may conclude that as short a variable resistance wire strain gage should be used for recording dynamic strains as is practical.

The time at which failure will take place in a beam and the location of the fracture are dependent on the superposition of all the harmonic vibrations present when the impact load is just sufficiently large to break the beam. An excessively large impact load will cause the beam to fail at, or before, the strain reaches its first peak. An immediate relief of stress takes place, in the close vicinity of the fracture only, when the beam fails.

The writer would like to make a few recommendations which might be helpful in future investigations. A cathode-ray tube with a short persistence fluorescent screen should be used in the oscilloscope so that pictures can be taken at a faster sweep rate of the oscilloscope. A complete record of each drop could be obtained if the output of the strain gage circuit were fed into the x-axis amplification of the oscilloscope and a high-speed continous motion camera were used for recording the dynamic strain.

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VITA

Niels B. Haubold, son of Dr. Werner R. Haubold and Charlotte R. Haubold, was born on June 6, 1934, at Wiesbaden, Germany. He received his elementary and secondary education in Germany, Austria, and in the United States. Upon graduating from the Senior High School at Palacios, Texas, the author registered at the University of Missouri, School of Mines and Metallurgy and was granted the degree of Bachelor of Science in Mining Engineering in May, 1957.