# A STRUCTURAL-DYNAMIC RESEARCH PROGRAM ON ACTUAL SCHOOL BUILDINGS

By

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## ABSTRACT

A comprehensive structural-dynamic research program involving fifteen existing school buildings in California has recently been completed after two years of work. The buildings are of one, two, and three-story construction and of various materials and combinations of materials, including wood, reinforced concrete, masonry, and steel. The research efforts included the calculation of the dynamic properties from the drawings, forced vibration of the buildings, reconciliation of the periods and damping coefficients obtained, and the electric analog response to four complete earthquake records. The elastic spectral responses obtained with the analog were reconciled by the reserve energy technique with provision for inelastic behavior, damping, energy dissipation, and period changes under large deformations.

The work of this investigation provides new information on spectral data in the short period range as well as on the probable behavior of low, rigid structures under California earthquakes. The results of the comprehensive investigation and report are summarized briefly in this paper.

## INTRODUCTION

The trend in architecture toward more glass and less inherent structural strength has raised many pertinent questions concerning the usual static methods used in designing low buildings. The California State Division of Architecture, after a few school buildings experienced partial damage from the Kern County shocks of July 1952 and the San Francisco March 1957 shock, felt that a random sampling of public school buildings should be analyzed by modern procedures and employing modern field measuring devices as well as be subjected to simulated earthquake motion. The general objective of the program was to evaluate to the greatest possible extent the effectiveness, adequacy, and economy of California's public school earthquake-resistant design requirements which must meet the minimum requirements of Title 21, California Administrative Code.

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This paper presents a synopsis of the results of continuous effort over the past two years by the John A. Blume & Associates Research Division. This work is covered in a 300-page report entitled "A Structural Dynamic Investigation of Fifteen School Buildings Subject to Simulated Earthquake Motion" by John A. Blume, Roland L. Sharpe, and Eric Elsesser.(1) The highlights of the complete report are presented herein.

Fifteen typical California school buildings were carefully selected for analysis, the properties of which are listed in Table 1. The buildings were individually investigated for answers to the numerous questions posed in the program objectives. The general question, of course, was how would these buildings react to various earthquakes in the light of current knowledge? The following procedure was established for the investigations:

First, an initial calculation of mass, spring factors (stiffnesses), and natural periods was made for each building.

Second, data was taken at the building sites to record the response of natural and/or forced vibrations.

Third, the buildings were converted to various equivalent dynamic systems using the building seismic weights, stiffnesses and damping values. These systems were subjected to four recorded earthquakes on an electric analog apparatus in order to obtain the range of elastic response to be expected.

Fourth, a review of the differences between calculated and measured natural periods provided some insight into the structural dynamic behavior and indicated changes necessary for more reliable calculations of stiffnesses and periods from the design drawings.

Fifth, the elastic analog shears were reconciled with the much lower Title 21 design coefficients by exploring the inelastic behavior range and the energy capacity of the buildings.

## ASSUMPTIONS FOR NATURAL PERIOD CALCULATIONS

The problems of analysis of low structures are compounded by the fact that they are not as easily represented by an equivalent mathematical, electrical, or mechanical system as are tall structures. As the number of stories or masses in a multi-mass structure increases the possible error inherent in any system chosen as equivalent, is proportionately reduced so that for the tall building the discrepancy between actual and equivalent systems diminishes; however, this is not necessarily true for low buildings which are very complex structures in the dynamic sense. Generally two uses have been made of building periods: (1) in a comparative manner to give a rough indication of the relative rigidity and mass of a structure with respect to other structures, and (2) to predict seismic forces from acceleration and velocity-period spectra. Neither use requires an exact determination of period since the resulting spectral accelerations used for design are not sensitive to small variations of period. For example, a variation of natural period in either direction by 20% will produce only a 5% change in the corresponding acceleration on the "standard spectrum" described later in the report.

The practical problem of estimating natural periods of actual buildings required some short cuts and generalizations which follow: (a) The total seismic weights were concentrated at the horizontal diaphragms; (b) The bending and shear deflection (per story) for each major structural element were calculated; (c) The basic material moduli E and G were initially considered as constant for deflection calculations regardless of variations of element proportions, quality of construction, age of construction and applied load; (d) The natural period was described by the combined cantilever-shear system,

$$T = 0.27 \sqrt{\frac{W}{K}} \quad (1)$$

and (e) The soil flexibility was found to influence only the transverse building period (short direction) by an amount which varies with the proportions of the building and the soil type (a long, narrow building and a soil with low bearing value, such as moist clay, produces the greatest lengthening of the natural period. This range of period increase varied from 5% to 20%.).

The calculation of natural periods, as outlined above, was based upon assumed elastic behavior. When and if the response passes into the inelastic range, as it might be expected to do during an earthquake, the periods will change unless the system is purely elasto-plastic. Exact calculation of inelastic-range periods is not always feasible; however, an estimate of the change of periods, and structural behavior in general, can be made by energy methods as discussed in the paper on Reserve Energy(2) (3).

## FIELD RECORDING OF BUILDING VIBRATIONS

Field vibration recordings were made of the school buildings with several types of recording instruments. The vibration records were later analyzed in detail to determine and isolate the natural building periods, the damping characteristics and the relative responses at various periods. The recorded vibrations were by wind and/or forced vibration with a shaking machine. It was found as expected, that prevailing winds at the building sites did not excite the low rigid buildings sufficiently to enable the recording instruments to pick up the small amplitude vibrations. On two occasions when there was sufficient wind to produce measurable amplitudes, however, the records were so confused with extraneous high frequency vibrations as to render them impossible to interpret. Therefore, the only reliable means of recording natural periods and obtaining data was to vibrate the buildings with a "shaking machine". The machine used was modified to have a maximum output of about 5,000 lbs. at a top speed of 1,200 RPM. It is the property of the U. S. Coast and Geodetic Survey, Seismological Division.

The vibrator was always positioned on the ground floor of one-story buildings and in the two and three-story buildings it was located on the floor immediately below the roof. It would have been informative to have positioned the vibrator on the roof of several buildings in order to have achieved larger amplitude vibrations; however, it was not practical to hold the machine in position in existing and occupied buildings without damaging the roofing. In several schools it was not possible to position the vibrator to induce longitudinal building motion nor in the most ideal (dynamic) locations. Figure 1 indicates typical vibrator installations and the precautions necessary to hold the machine in place during a shaking test. In general, it was difficult to vibrate such rigid buildings without causing damage to the finished surfaces.

Several types of recording devices were employed which included vibration meters, a Sanborn Recording Oscillograph, a Brush Recording Oscillograph, and two Sprengnether Portable Seismographs.

The vibration records, samples of which are shown in Figure 2, were analyzed by scaling the trace periods, reading the amplitudes with a microscope for each component of each vibrator run, and then plotting normalized amplitude versus period for all significant records. Sample of a normalized curve is given in Figure 3.

## ELECTRIC ANALOG ANALYSIS

Another phase of the investigation consisted of subjecting the buildings to four simulated earthquakes taken from four actual earthquake records. This was done by means of an electric analog located at the Dominion Physical Laboratories, Lower Hutt, New Zealand. These particular earthquake records were selected from accelerograms recorded by the U. S. Coast and Geodetic Survey because they represent complete records of strong seismic motion which has produced damage to structures. Table 2 lists the characteristics of the earthquakes used in this series. The analog used is described in a paper by Murphy, Bycroft and Harrison (4).

## SUMMARY OF PERIOD CALCULATIONS

The elastic stiffnesses and fundamental periods of the school buildings were calculated using the assumptions previously mentioned. Two basic foundation conditions were used for each building. The first assumed the building to be founded on a rigid, non-yielding foundation material, and the second assumed a flexible foundation material on which the building was permitted to rotate. The latter approximates actual conditions for many buildings. Table 3 summarizes the comparison of calculated and measured periods.

The calculated low-amplitude periods listed on Table 3 for all of the buildings investigated ranged from a low of 0.02 seconds for a rigid one-story building to a high of 0.20 seconds for a flexible one-story building. This is a relatively narrow range considering the radically different structural systems investigated. This indicates that perhaps only a generalized period value is needed for a particular type of construction, one which falls within an acceptable range of values. It is interesting to note that this maximum range of period values occurs with the one-story buildings, and does not include the three-story building which would have been expected to have the longest natural period of all the buildings investigated. It is the two extremes of the structural types involved, rigid concrete block and flexible steel rigid frame which account for the extremes of calculated periods.

In many buildings the non-structural elements (plaster, partitions, glass, etc.) provide a substantial part of the total calculated lateral stiffness. (See Table 4.) This tabulation indicates for flexible structures, such as Building 3, that all of the building elements will participate in resisting earthquake forces. Their connections to the building frame should therefore be properly and carefully detailed. The elements could be made "floating", i.e., so the frame could deflect without severely stressing the partitions and glass. Or if desired, the partitions could be designed to resist a certain amount of lateral force such as that caused by moderate earthquakes or wind. Obviously, the non-structural items would not participate to a great extent in rigid buildings such as those at Buildings 5 or 6.

The method used to calculate the natural periods, produced reasonable results that are within the range of measured periods. (See Table 3.) It is felt, therefore, that the assumptions made are valid and the method used can be applied to low buildings in general, even though a particular structural type in question may not have been investigated for the report. Several of the important problems in the adequate calculation of a period are: (1) selection of an appropriate modulus of elasticity and modulus of rigidity for deflection; (2) evaluation of foundation rocking and selection of a soil modulus[7]; and (3) selection of an equivalent mathematical model.

A very simple method of estimating the period of typical California school buildings was also developed and is shown in Table 5. This is considered adequate for design purposes.

## STRUCTURAL DAMPING

From the normalized forced vibration resonance curves selected, resonant peaks corresponding to the building periods were replotted to larger scales without normalizing the amplitude, (see Figure 4 and Figure 5) thus making it possible to calculate damping values. The method used, which is approximate, simply requires a knowledge of the ordinates of the resonant envelope curve. The damping, in terms of percent of critical, was calculated by this method and is summarized in Table 6 for those buildings for which adequate records were available.

## ANALOG SHEAR VALUES FOR SIMULATED EARTHQUAKES

Figure 6 indicates the maximum values of analog acceleration for one, two and three-story buildings subjected to the four simulated earthquakes with damping as a parameter. The results for a single-mass system under El Centro 1940 (N-S), are shown in Figure 7 and under Olympia 1949 in Figure 8.

From inspection of Figure 9 the following trends for elastic response of one-story buildings are observed:

(1) There is a general increase in acceleration values corresponding to a lengthening of period within the period range investigated (0.03 to 0.25 for all damping values and for all four earthquakes).

(2) The elastic analog accelerations are many times greater for one-story buildings for the four earthquakes investigated than the Title 21 coefficient of 0.13% g.

(3) The more rigid buildings (concrete and masonry construction) fall into the very short period range while the more flexible (wood or steel frame) fall into the longer period range; consequently, the rigid buildings experienced lower accelerations than did those of flexible construction. This is a phenomenon of the short-period building elastic response to the four earthquakes which is in contrast to taller buildings (having periods greater than 0.25 seconds) which experience the opposite pattern of behavior; namely, lower accelerations for more flexible construction.

Other investigators[6] using different equipment have also obtained elastic accelerations for a one-mass oscillator, spectrum curves for $n = 2\%$ and 20% for the El Centro 1940 earthquake and have been ploted for comparison with this analog in Figure 10. The two sets of spectral accelerations are in good agreement.

The trends to be observed from the 2 and 3 story analog data are, in general, similar to those for single-story buildings; however, two additional points are noted:

(1) The progression of acceleration values with change of period is more chaotic, depending more upon building geometry, the relative distribution of stiffness and weight between the stories, and the characteristics of the particular earthquake.

(2) The measured base accelerations of the two and three-story buildings, although somewhat erratic, appear to be slightly less than for the one-story buildings; however, the acceleration of the top story in multi-story buildings is greater than for the single story buildings.

It was noted from the various plots for both single and multi-mass systems that the acceleration values would not be significantly changed by any period errors, even of appreciable magnitude. Moreover, any increase in the damping values, which may (or may not) be possible with greater amplitude of motion would not appreciably decrease the acceleration values.

It is obvious that a strength safety factor alone can not account for the great difference between elastic design values and elastic analog accelerations for these four earthquakes. Greater earthquakes than these can occur, which fact further increases the problem. However, current design coefficients do not necessarily have to be increased. A better approach is to investigate energy demands with both elastic and inelastic considerations.

This was done for six of the buildings in the research program with the Reserve Energy technique[2] [3]. Figure 11 presents a plot of this technique for Building No. 2.

## SUMMARY AND CONCLUSIONS

The results of this research into the structural dynamic behavior of California School Buildings when subjected to simulated earthquake motion are many and varied. Because of the apparent unrelated nature of some of the work found necessary to pursue the subject, the summary and conclusions are divided into categories and are presented in part from the original report. Although the conclusions have been derived from work on low, rigid school buildings, they could be applied in general and with few reservations to other low, rigid building construction in earthquake areas.

### A. Regarding Natural Periods of Vibration

(1) School buildings in general possess relatively short natural periods of vibration, that is, below 0.25 seconds. The range of measured natural periods at small amplitudes, varied from 0.05 seconds for the extremely rigid one-story masonry or concrete buildings tested in this work to 0.17 seconds for the one-story wood frame buildings. The two and three-story building fundamental mode periods were all below 0.15 seconds.

(2) The numerous and variable complexities involved in the calculation of "accurate" natural periods of low buildings, and the relatively small variation in the building periods reported herein, indicate that school building periods can be adequately and simply estimated by multiplying the number of stories by factors which vary with the type of construction. (See Table 5).

(3) The laterial period of a building element such as a long, narrow roof system may be longer than that of the structure as a whole and tend to dominate the response to an earthquake.

(4) A variation, in the accuracy of a building period, of as much as 20% for example, is relatively unimportant when the period is used to evaluate response from an acceleration spectrum.

### B. Regarding the Field Vibration Tests

(1) The forced vibration field work generally produced natural periods (see A-1 above) and damping values applicable to and valid for the small-amplitude range of behavior. Slight increases in both periods and damping would be expected during actual seismic motion in the elastic range; greater lengthening of period would be expected in the inelastic response to severe ground movements.

(2) It was found impractical to measure reliable natural periods of these rigid buildings by other means than forced vibration. Wind

or traffic as disturbing forces did not produce a sufficient range or intensity of motion. Push or pull tests were not feasible because of possible damage to finishes.

(3) Correlation between calculated and measured periods was generally good and was better for wood frame buildings than for rigid concrete buildings. Variations in the material and soil constants, and in the "elastic" modulus over the range of loading account in large measure for the discrepancies.

(4) The damping values obtained from the resonance curves for the small-amplitude range vary from 1.9 to 12.4% of critical. The average of eighteen determinations was 5.6%.

C. Regarding the Analog Results (Elastic Assumption)

(1) The equivalent seismic shears produced by the electric analog from four actual earthquakes records describe the "elastic" building behavior in the very short period range and provide a basis for estimating the inelastic behavior, knowledge of which is essential in order to provide economical aseismic resistance for several types of school buildings.

(2) The school building periods are shorter than the peak values on earthquake spectra. Thus the response acceleration falls between that of the ground and that of the spectral peak, with the longer building periods and lengthening building periods (due to yield or damage) approaching the high values.

(3) The seismic shears (30% g to 70% g) resulting from the "elastic" exposure to the earthquake records are several times in excess of specified elastic code coefficients for the same buildings.

(4) Generally, the elastic acceleration response of the more rigid school buildings is less by as much as one-half than the corresponding response for flexible school construction.

(5) Damping plays an important part in determining the accelerations except at the very short period range. Large values of assumed damping (10% to 20%) produce lower spectral accelerations at a given period than do small values of damping (2% to 5%); however, (a) the value of damping has a minor influence on acceleration in the shorter period ranges (below 0.06 seconds) where the buildings are responding almost directly to the ground motion, regardless of damping, and (b) the spectral response does not decrease directly with damping. Damping alone does not reconcile current practice and the seismic risk.

(6) Elastic deflections which were calculated from analog shears for the El Centro 1940 earthquake ($n = 5\%$) are quite small, ranging from 0.04 to 0.33 inches for all types of school buildings, and serve only as a relative indication of the behavior to be expected

during an earthquake if the building remains elastic. The buildings can only remain elastic if so strong and rigid as to develop adequate energy without cracking or yielding.

(7) Soil compliance may affect the response in two basic ways: by lengthening the natural period and by dissipating some of the seismic energy. The former has been evaluated but the latter has not. It is believed that any tendency toward less response (from energy "feed-back") would be (a) relatively minor, and (b) would be compensated in general by the fact that the building periods calculated tend to be short (in the low-amplitude phase of elastic response) and on the ascending side of the spectral peak.

D. Regarding School Buildings as Currently Designed and Constructed

The following conclusions are based upon the intensive study of fifteen buildings in the program. Although there is a wide variation in the types of California school buildings, those selected are considered as typical examples and, as a group, to provide a reasonable basis for generalization, except as may be otherwise noted.

(1) School buildings as actually constructed have lateral elastic strength values, especially in walls, greater than the requirements of Title 21. The amount of this "excess" value was found to be quite variable between buildings. For the thirteen types considered the total "static" value, at code allowable unit stresses, ranged from 0.16 g to 1.40 g. The wall disposition and the basic layout together with minimum practical wall thicknesses are principal factors in the amount of resistance.

(2) In spite of the "excess" value noted in D (1) above, three of the buildings investigated would be stressed beyond the yield point under the assumption of elastic response if subjected to the 1940 El Centro earthquake as recorded 30 miles from its epicenter.

(3) Except for the very strong and rigid concrete or masonry school buildings without appreciable glass areas, action within the elastic range can not be depended upon for resistance to a major earthquake. The more flexible structures must react in the inelastic range and deflect appreciably to develop adequate energy absorbing capacity. Although there may be some residual deflection and/or cracking such can be considered as an economic method of resistance, considering the probabilities, provided care is taken to prevent injury from local damage.

(4) The ultimate reserve energy capacity of the six buildings so analyzed, appears to vary from barely adequate to 36 times required resistance for the El Centro "standard" spectrum. This energy value is considered a better indication of true resistance than "static" design value.

(5) The apparent real resistance of all but the very strong and rigid school buildings is not necessarily proportional to the "elastic" design resistance or coefficients. It is possible to have two different buildings, even of similar materials, each designed to Title 21, with vastly different ultimate "static" resistance and also ultimate dynamic resistance to major earthquakes. The principal parameters are the number and extent of walls including the openings together with the provisions for reserve ductility, strength, and structural integrity.

(6) The more flexible type school construction such as with "cantilevered" mullions, glass walls, lightly braced framing and long narrow diaphragms even though passing Title 21 requirements, is more vulnerable to damage of both a structural and non-structural nature than the more rigid construction. (This is the reverse of tall building phenomena and should not be confused with same. Refer to Figure 9.)

(7) Typical school buildings, unlike taller buildings with longer natural periods of vibration, are improved in seismic resistance with greater rigidity as well as strength; conversely, as a result of damage from earthquake motion, their lengthening periods advance into the more critical range of spectral exposure rather than the less critical as is the case for buildings of longer initial periods.

(8) Elements such as roof and floor diaphragms should be kept rigid, their transverse natural periods should be well below 0.15 seconds, or be especially designed for dynamic response. Long, narrow diaphragms tend to have periods that "tune" in to the most critical part of the earthquake spectrum. Not only are such elements subject to damage, but their reactions affect adjoining parts such as wall supports.

(9) "Non-structural" elements were found to provide initial resistance to lateral deflection the contribution of which ranged from 0% to 96% of total initial resistance in the various buildings considered. Depending upon the severity of ground motion and the building resistance required, such weak elements attempt to provide the resistance and usually must crack, yield or otherwise "fail" to allow the structural walls and/or framing to perform as intended. All elements, the breakage of which would be dangerous or costly, such as glass walls and partitions, should be carefully detailed so as not to resist the movement, i.e., to allow the structure to deflect as necessary.

E. <u>Regarding the Earthquake Exposure</u>

(1) The exposure to earthquakes in California is such as to suggest the 1940 El Centro record "standardized" shown on Figure 9 as a logical goal for school building resistance. Since this was recorded 30 miles from the epicenter and a great many California schools are closer than 30 miles to active faults, the suggestion

cannot be considered conservative. The probability of shocks like El Centro 1940 or greater have been estimated as 63 times in 200 years somewhere in California, and 2.6 times in 200 years at any specific locality in California[6].

(2) Some damage and yield should be expected in resisting severe earthquakes centered fairly close to the epicenter, except for very rigid and strong construction of low period and having a generous area of structural walls in both directions.

(3) Although the 1940 El Centro earthquake as recorded was more severe than the other three considered, for the range of periods involved in the school buildings, the other earthquakes were only slightly less critical or severe.

F. Regarding the Cost of Earthquake Resistance

(1) The difference between school construction costs for minimum good construction practice and for code aseismic resistance generally amounts to no more than 1% of the total building cost. Building code requirements for vertical and wind loads together with the geometric properties often cause a low school building to have such lateral load capacity that the cost of meeting code earthquake requirements is negligible.

## ACKNOWLEDGEMENTS

The California State Department of Public Works, Division of Architecture, Anson Boyd, State Architect, through its research funds made possible the major portion of the program; however, as the program developed, it became evident that additional work should be performed and costs incurred to further substantiate certain results and conclusions. This was contributed by John A. Blume and Associates Research Division who planned and conducted the research program with the cooperation of Division of Architecture representatives. Cooperation was also received from the United States Coast and Geodetic Seismological Field Survey, the New Zealand Dominion Physical Laboratory, and many school officials.

## NOMENCLATURE

T - Natural period, seconds, transverse

K - Stiffness, pounds per inch

W - Weight, pounds

n - Percent of critical damping

E - Modulus of elasticity pounds per square inch

G - Modulus of rigidity pounds per square inch

RC - Reinforced concrete

DS - Diagonal sheathing

L - Longitudinal

## BIBLIOGRAPHY

(1) Blume, Sharpe, & Elsesser, "A Structural-Dynamic Investigation of Fifteen School Buildings Subjected to Simulated Earthquake Motion", for the State of California, Department of Public Works, Division of Architecture (being printed).

(2) Blume, John A., "Structural Dynamics in Earthquake-Resistant Design", Proceedings ASCE, ST4, No. 1695, July 1958 and Closure to Discussion of 1695, September 1959.

(3) Blume, John A., "A Reserve Energy Technique for the Earthquake Design and Rating of Structures in the Inelastic Range", Second World Conference on Earthquake Engineering, Tokyo, Japan, July 1960.

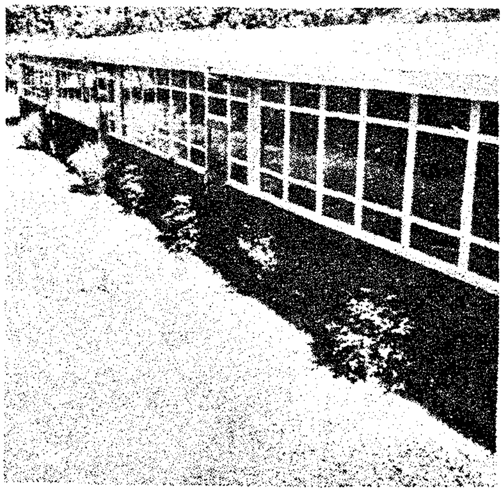
(4) Murphy, Bycroft, and Harrison, "Electrical Analogy for Earthquake Shear Stresses in a Multi-Story Building", Chapter 9, Proceedings, World Conference on Earthquake Engineering, June 1956; EERI, Room 1039, 465 California Street, San Francisco, California.

(5) Alford, Housner and Martel, "Spectrum Analyses of Strong-Motion Earthquakes", Officeof Naval Research, Contract N 6 ONR-244, August 1951.

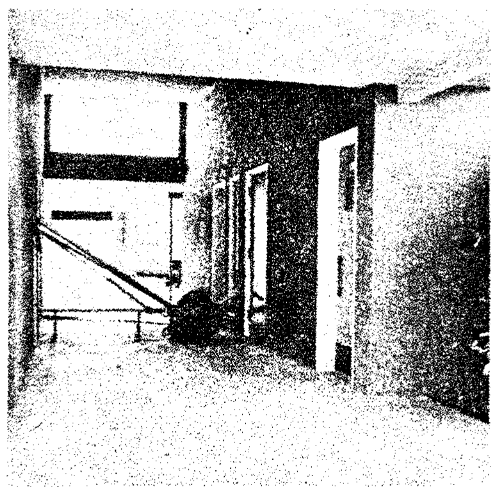
(6) Housner, G. W., "Intensity of Ground Motion During Strong Earthquakes", Office of Naval Research, Contract N60 NR-244, August 1952.

(7) Goto, H., Report I, "Rocking Vibration of School Buildings Located on Elastic Ground", April 1959; Report II, "Vibration Analysis of School Buildings Considering the Vibrating Mass of Soil", August 1959 (unpublished: done in connection with this research program).

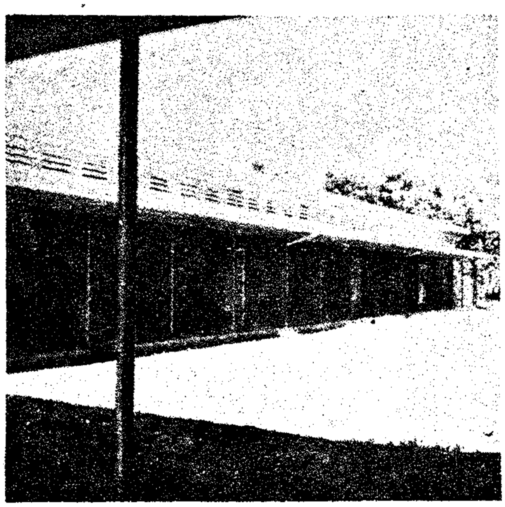
(8) U. S. Forest Products Laboratory Report 2082, "Diaphragm Action of Diagonally Sheathed Wood Panels", November 1957.



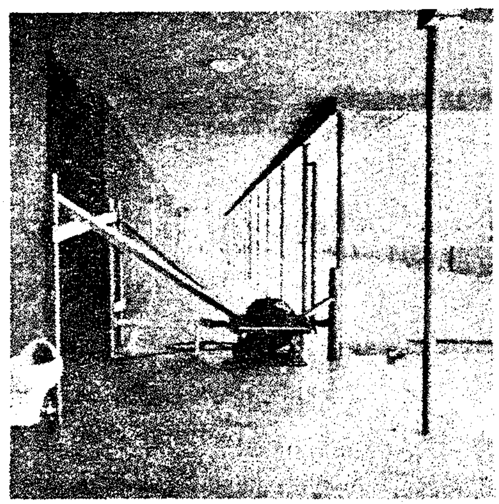
(a) North Elevation



(b) Vibrator in Position for Longitudinal Shaking



(c) South Elevation



(d) Vibrator in Position for Transverse Shaking

BUILDING NO. 2

FIG. 1

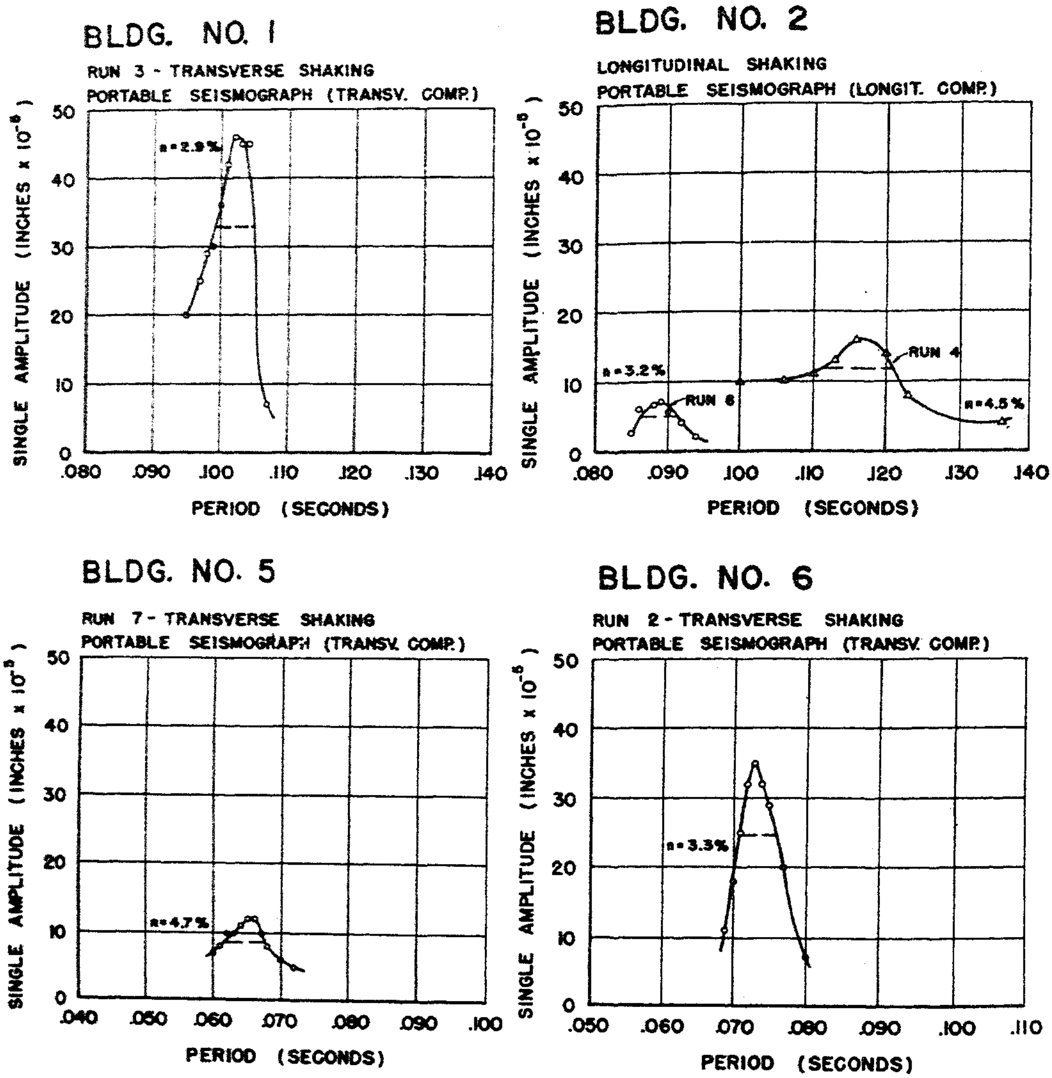



FIG. 4 SELECTED RESONANCE CURVES FOR 1-STORY BUILDINGS USED FOR DAMPING CALCULATIONS

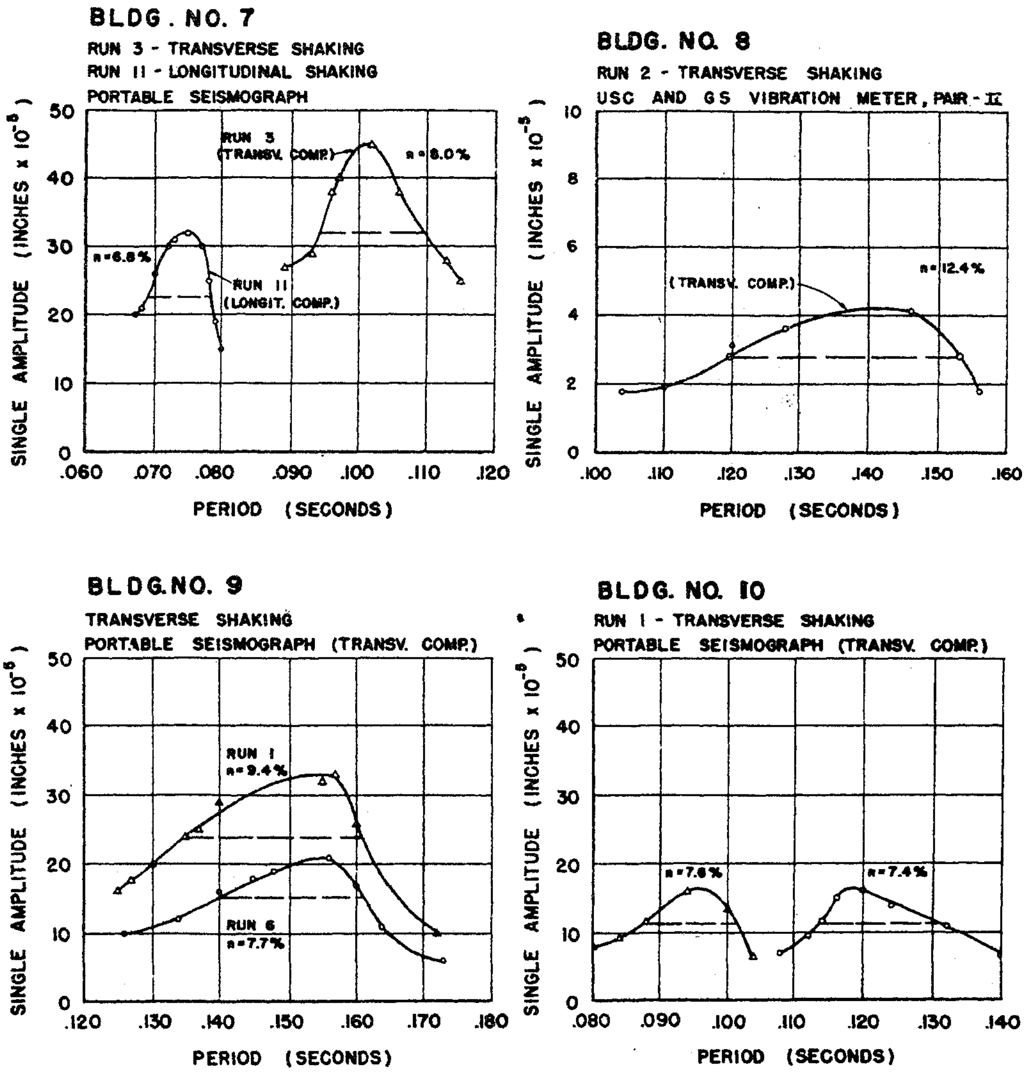



FIG. 5 SELECTED RESONANCE CURVES FOR 2 AND 3 STORY BUILDINGS USED FOR DAMPING CALCULATIONS

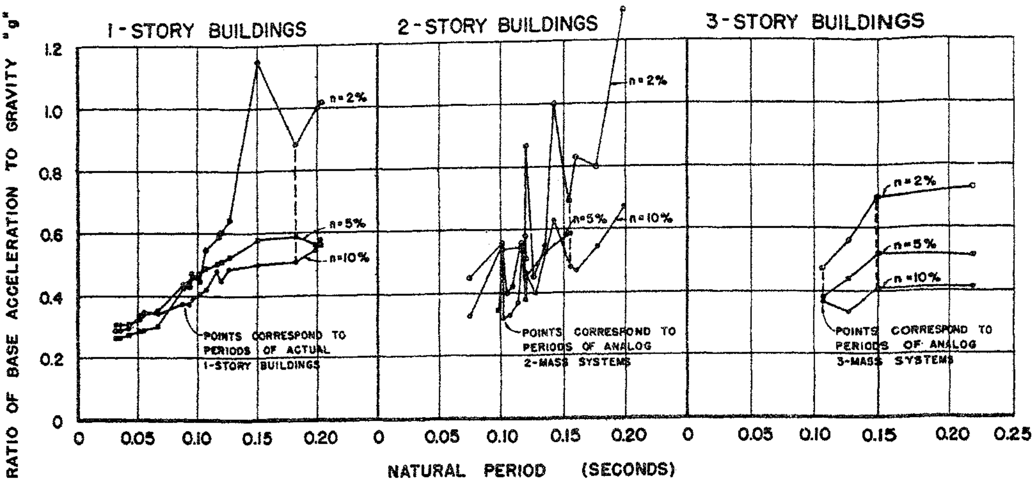



FIGURE 6 — MAXIMUM VALUES OF ANALOG ACCELERATION FOR 1-STORY 2-STORY AND 3-STORY BUILDINGS SUBJECTED TO FOUR SIMULATED EARTHQUAKES

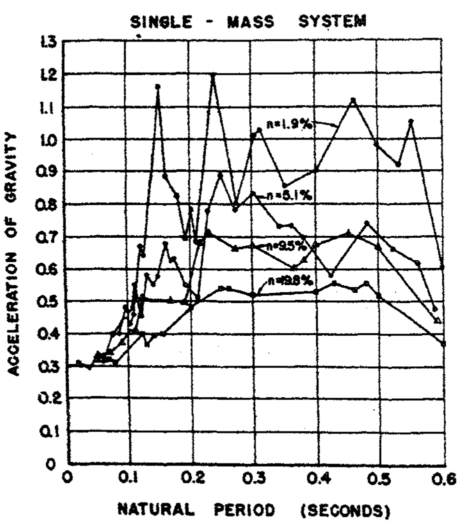



FIG. 7 ACCELERATION SPECTRA FOR EL CENTRO (N-S) EARTHQUAKE OF MAY 18, 1940

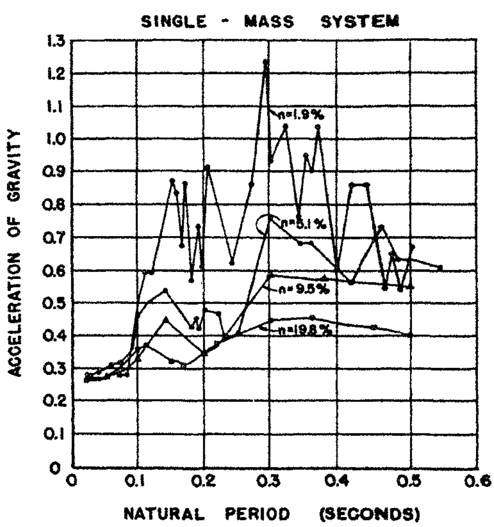



FIG. 8 ACCELERATION SPECTRA FOR OLYMPIA (S 80 W) EARTHQUAKE OF APRIL 13, 1949

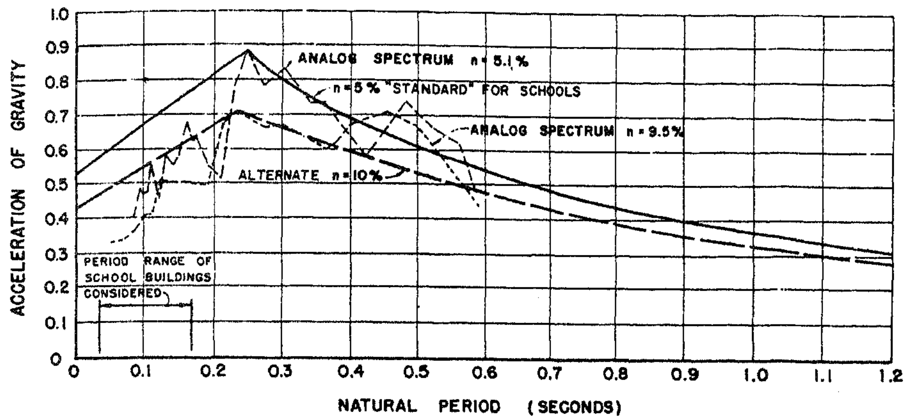



FIGURE 9 — "STANDARD" ACCELERATION SPECTRA BASED UPON SINGLE-MASS ANALOG DATA FOR EL CENTRO (N-S) EARTHQUAKE OF MAY 18, 1940

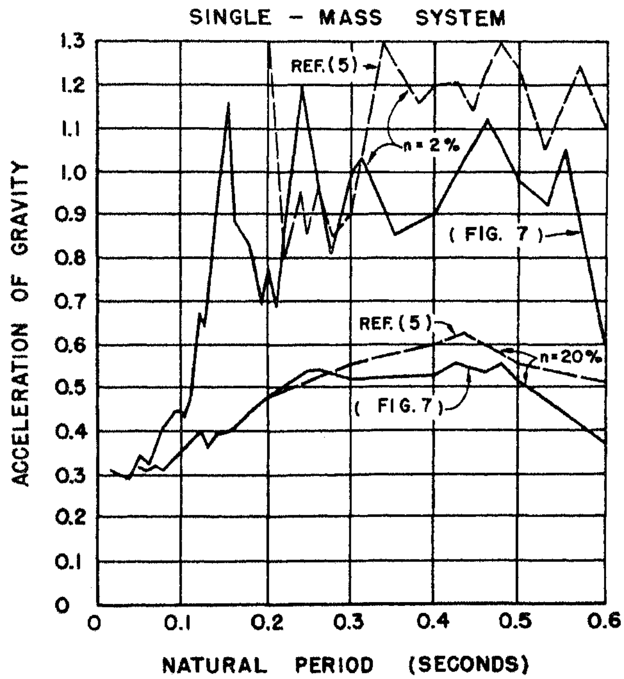
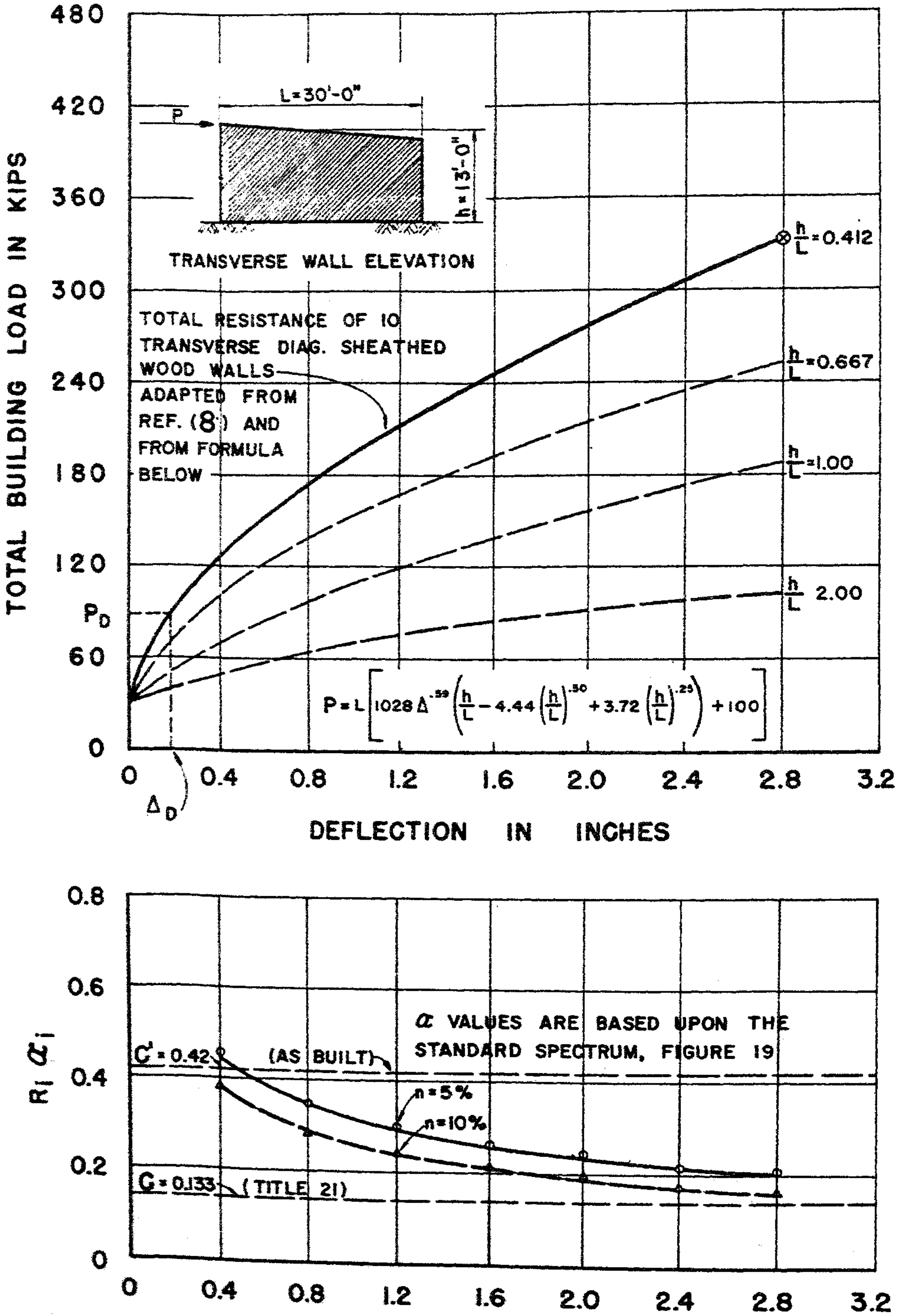



FIG. 10 COMPARISON OF SINGLE-MASS ACCELERATION SPECTRA FROM TWO SOURCES FOR EL CENTRO (N-S) EARTHQUAKE OF MAY 18, 1940




# RESERVE ENERGY TECHNIQUE BLDG. #2
FIG. 11

Table I

Primary Lateral Load Resisting Elements

| Building No. | Vertical Elements: Transverse | Vertical Elements: Longitudinal | Horizontal Elements |
|---|---|---|---|
| **One Story** | | | |
| 1, Classrooms | 1" DS & 3/8" Plywood shear walls | 3/8" Plywood | 1" DS Roof |
| 2, Classrooms | 1" DS Shear walls | 4x6 Wood Window Mullions Cantilevered from 1" DS Walls | 1" DS Roof |
| 3, Classrooms | Steel Rigid Frame | Steel Rigid Frame | 1" DS Roof |
| 4, Multi-Use | Steel Rigid Frame & 1" DS shear walls | 10WF Columns Cantilevered from 1" DS Walls | 2x4 Solid Laminated Roof |
| 5, Gymnasium | 6" RC Shear Walls & RC Rigid Frames | 6" RC Shear Walls | $2\frac{1}{4}$" Poured Gypsum Roof |
| 6, Kindergarten | 8" RC Block Shear Walls, all Cells Filled | 8" RC Block Shears Walls, all Cells Filled | 1" DS Roof |
| **Two Story** | | | |
| 7, 2-story Admin. Building | 8" RC Shear Walls with Brick Veneer | 8" RC Shear Walls with Brick Veneer | Roof: Concrete Slab & Steel Joist Floor |
| 8, 2-story Classroom Building | 9" & 10" RC Shear Walls & Frame | 10" RC Shear Walls & Frame | Roof & Floor: Concrete Slab & Joist |
| 9, 2-story Classroom Building | 8" RC Shear Walls & Rigid Frame | RC Rigid Frame with $8\frac{1}{2}$" RGBM Filler Walls | Roof & Floor: Concrete Slab & Joists |

Table 3

Comparison of Calculated and Measured Periods

| School | Transverse: Calculated Rigid Fdn. (Sec) | Transverse: Calculated Flex. Fdn.* (Sec) | Transverse: Measured Period (Sec) | Longitudinal: Calculated Rigid Fdn. | Longitudinal: Calculated Flex. Fdn.* | Longitudinal: Measured Period (Sec) | Measured Roof (As a Beam) (Sec) |
|---|---|---|---|---|---|---|---|
| 1 | .091 | .101 | .102 | .094 | .094 | — | |
| 2 | .088 | .091 | .089 | .128 | .128 | .118 | |
| 3 | .085 | .106 | — | .202 | .202 | — | |
| 4 | .101 | .182 | — | .190 | .200 | — | |
| 5 | .049 | .055 | .066 | .050 | .053 | — | .095[a] |
| 6 | .023 | .050 | .052 | .024 | .033 | — | .100[a] |
| 7 | .065 | .091 | .100 | .077 | .081 | .076 | .25[b] |
| 8 | .095 | .101 | .140 | .066 | .067 | — | |
| 9 | .094 | .119 | .150 | .077 | .081 | .102 | |
| 10 | .077 | .095 | .120 | .100 | .103 | .095 | .250[b] .250[b] |
| 11 | .072 | .089 | .090 | .094 | .131 | .126 | |
| 12 | .072 | .090 | .089 | .094 | .133 | .126 | |
| 13 | .072 | .097 | .087 | .094 | .148 | .113 | |
| 14 | | | | | | | |
| (Stage 1) | — | — | — | .145 | .165 | .165 | |
| ( " 2) | .030 | .035 | .108(?) | .048 | .055 | .130(?) | |
| ( " 3) | .027 | .032 | — | .036 | .041 | .128(?) | |
| 15 | | | | | | | |
| (Stage 1) | .080 | .098 | .080(?) | — | — | .168 | .315[a] |
| ( " 2) | .086 | .105 | .077(?) | .126 | .129 | .108 | .192[a] |
| ( " 3) | .095 | .117 | — | .175 | .179 | .150 | .143[a] |

* Value used in determining the ratio of calculated/measured.
a Vertical Motion
b Horizontal Diaphragm

Table 4

"Nonstructural" Stiffness As a Percentage of Total

| School | | Transverse | Longitudinal |
|---|---|---|---|
| 1 | | 18% | 33% |
| 2 | | 0% | 26% |
| 3 | | 96% | 91% |
| 4 | | 25% | 24% |
| 5 | | 0.1% | 0.2% |
| 6 | | 0% | 0% |
| 7 | Second Story | 7.3% | 0% |
| | First Story | 4.5% | 2.8% |
| 8 | Second Story | 4.9% | 0% |
| | First Story | 1.7% | 0% |
| 9 | Second Story | 1.6% | 0% |
| | First Story | 1.6% | 0% |
| 10 | Third Story | 3.6% | 10.7% |
| | Second Story | 3.3% | 10.7% |
| | First Story | 0.9% | 2.17% |
| 11, 12, 13 | | 0% | 0% |
| 14 | | 0% | 0% |
| 15 | | 23% | 0% |

Table 5

Proposed Determination of Natural Periods of Low Buildings

One-Story School Buildings

| Type * | Period T |
|---|---|
| Concrete Shear Wall | 0.05 seconds |
| Masonry Shear Wall | 0.05 seconds |
| Wood Shear Wall | 0.10 seconds |
| Cantilevered Wood Mullions | 0.12 seconds |
| Rigid Steel Frame | 0.15 seconds |

Two and Three-Story School Buildings, Transverse Direction

| Type * | Period T |
|---|---|
| Concrete Shear Wall | 0.05 x N seconds |
| Masonry Shear Wall | 0.05 x N seconds |
| Concrete Frame | 0.07 x N seconds |

Where N = number of stories

Two and Three-Story School Buildings, Longitudinal Direction

| Type * | Period T |
|---|---|
| All construction | 0.4 x N seconds |

* In the direction under consideration.

Table 6

Percentage of Critical Viscous Damping
From Recorded Resonance Curves

| School | Transverse Direction n | Transverse Direction % "g" of Vibrator Force @ Resonant T | Longitudinal Direction n | Longitudinal Direction % "g" of Vibrator Force @ Resonant T |
|---|---|---|---|---|
| 1 | 2.9 | .17 | - | - |
| 2 | - | .22 | 3.2, 4.5 | .13 |
| 3 | - | - | " | - |
| 4 | - | - | - | - |
| 5 | 4.7 | .08 | - | - |
| 6 | 3.3 | .82 | - | - |
| 7 | 8.0 | .08 | 6.8 | .02 |
| 8 | 12.4 | .01 | - | .02 |
| 9 | 7.7, 9.4 | .02 | - | .04 |
| 10 | 7.9 | .01 | 7.6 | .01 |
| 11 | - | - | 8.4 | .91 |
| 12 | 7.6 | 1.78 | - | .91 |
| 13 | 8.6 | 1.94 | - | .81 |
| 14 | | | | |
| (Stage 1) | - | .30 | - | - |
| (Stage 2) | - | .37 | - | .52 |
| (Stage 3) | - | .28 | 1.9 | - |
| 15 | | | | |
| (Stage 1) | 1.9 | 1.26 | 4.2 | .30 |
| (Stage 2) | - | 1.14 | 3.2 | .59 |
| (Stage 3) | - | - | 4.2 | .15 |

Table 7

Elastic Lateral Building Deflections Corresponding to Analog Shears From El Centro (N-S) Earthquake of May 18, 1940

| School | | Transverse Direction | | | | Longitudinal Direction | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | n = 5% | | n = 10% | | n = 5% | | n = 10% | |
| | | Δ * | %g | Δ * | %g | Δ * | %g | Δ * | %g |
| 1 | | .067" | 47 | .057" | 40 | .050" | 47 | .040" | 38 |
| 2 | | .047" | 43 | .040" | 37 | .088" | 46 | .084" | 44 |
| 3 | | .075" | 49 | .063" | 41 | .328" | 53 | .351" | 57 |
| 4 | | .269" | 59 | .228" | 50 | .322" | 53 | .334" | 55 |
| 5 | | - | - | .020" | 34 | - | - | .013" | 34 |
| 6 | | - | - | .011" | 33 | - | - | .004" | 30 |
| 7 | Second Floor | .078" | 45 | .074" | 42 | .163" | 123 | .162" | 122 |
| | First Floor | .044" | 35 | .043" | 34 | .035" | 57 | .035" | 56 |
| 8 | Second Floor | - | - | .159" | 48 | - | - | .042" | 58 |
| | First Floor | - | - | .102" | 41 | - | - | .030" | 48 |
| 9 | Second Floor | - | - | .196" | 53 | - | - | .076" | 39 |
| | First Floor | - | - | .139" | 42 | - | - | .055" | 33 |
| 10 | Third Floor | .144" | 46 | .139" | 44 | .123" | 57 | .089" | 40 |
| | Second Floor | .127" | 42 | .123" | 41 | .102" | 53 | .074" | 39 |
| | First Floor | .086" | 38 | .084" | 37 | .037" | 44 | .027" | 33 |
| 11, 12, 13 | | .049" | 44 | .041" | 37 | .112" | 51 | .106" | 49 |
| 14 (Stage 3) | | - | - | .004" | 30 | - | - | .007" | 30 |
| 15 (Stage 3) | | .043" | 49 | .042" | 48 | .179" | 58 | .154" | 50 |

* Total Building Deflection about Foundation

Table 8

Analog Acceleration Corresponding to Measured Damping of Buildings Subjected to 4 Simulated Earthquakes

| School | Comp. | Period (Sec) | Measured Damping n | Analog Base Acceleration % g Earthquake (a) | | | |
|---|---|---|---|---|---|---|---|
| | | | | I | II | III | IV |
| 1 | T | .102 | 2.9 | 45 | 50 | 40 | 22 |
| | L | .094* | - | - | - | - | - |
| 2 | T | .089 | - | - | - | - | - |
| | L | .118 | 4.0 | 50 | 53 | 37 | 28 |
| 3 | T | .106* | - | - | - | - | - |
| | L | .202* | - | - | - | - | - |
| 4 | T | .182* | - | - | - | - | - |
| | L | .200* | - | - | - | - | - |
| 5 | T | .066 | 4.7 | 34 | 28 | 31 | 23 |
| | L | .053* | - | - | - | - | - |
| 6 | T | .052 | 3.3 | 32 | 29 | 31 | 22 |
| | L | .033* | - | - | - | - | - |
| 7 | T | .100 | 8.0 | 35 | 36 | 39 | 22 |
| | L | .076 | 6.8 | 57 | 33 | 37 | 19 |
| 8 | T | .140 | 12.4 | 40 | 37 | 30 | 22 |
| | L | .067* | - | - | - | - | - |
| 9 | T | .150 | 9.0 | 44 | 43 | 39 | 27 |
| | L | .102 | - | - | - | - | - |
| 10 | T | .120 | 7.9 | 38 | 32 | 30 | 23 |
| | L | .095 | 7.6 | 38 | 32 | 29 | 22 |
| 11, 12, 13 | T | .090 | 8.2 | 39 | 32 | 30 | 22 |
| | L | .126 | 8.4 | 50 | 44 | 33 | 26 |
| 14 (Completed) | T | .032* | - | - | - | - | - |
| | L | .041* | 1.9 | 28 | 29 | 30 | 22 |
| 15 (Completed) | T | .117* | - | - | - | - | - |
| | L | .150 | 4.2 | 68 | 63 | 51 | 32 |

* Calculated values.
(a) Earthquake: See Table 2 for identification.