HANDBOOK FOR DETERMINATION OF RESPONSE OF
SHEAR BUILDINGS TO AN EARTHQUAKE

by *R.I. Skinner, **K.M. Adams and ***K.J. Brown

1. INTRODUCTION

An acute demand exists for methods whereby large structures subjected to rapidly fluctuating forces may be designed with a facility comparable to that enjoyed when designing to withstand static forces. In order to be efficient, such techniques must be precise and limited only by the uncertainties in the prediction of the fluctuating forces which will occur.

As a contribution to the simplified dynamic design of structures a handbook is being prepared which gives, for any one of an extensive range of buildings, the forces and motions which are generated within them by several of the largest recorded earthquakes. The building types covered include those which deflect laterally in shear, bending, mixed shear and bending, and those which deflect with flexing floors. The building data which the design engineer must obtain, in order to apply the handbook to a particular building, are the effective floor masses, the interstorey stiffnesses and an estimate of the damping factor of the normal modes.

This paper describes the two handbook parts which are used to obtain the responses (shear force, bending moment, displacement) of tall buildings which deflect in shear. The first part gives the responses, to a static base acceleration g, of the normal modes of a large range of shear buildings. These responses are given at each floor. Natural periods are also included. The second part of the handbook gives the responses of these normal modes to the ground motions of a number of the largest recorded earthquakes. A selection of the shear-building normal modes is given here, together with some of their responses to the earthquake recorded at Taft, California (N. 21 E. 21.7.1952) hereinafter referred to as the Taft earthquake.

A justification of the normal mode approach to assessing building responses is given in a companion paper presented at this conference - "Paper A"[1] Skinner, Adams and Brown. The conceptual and practical advantages of the normal mode approach are discussed and some of these

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will become evident in the present paper. A very practical advantage is the simplicity and accuracy with which the normal mode properties may be obtained from model or analogue measurements.

2. Idealized Building - Normal Modes

The idealized shear building used for analysis, Fig. 1(a), has the masses concentrated at the floors and deflects in pure shear, that is without tilting or flexure of the floors. Shear stiffness is independent of lateral deflection. Velocity damping, without mode interaction, is assumed. The base moves inexorably without tilting.

The movements of such a shear building of N stories may be resolved into motion of N independent normal modes each with an accompanying shear force and bending moment distribution. We will use the following normal mode properties, proved by Rayleigh [2] and discussed in Paper A [1].

(i) A normal mode moves with all mass accelerations in phase or in antiphase and hence inertia forces may be added algebraically.

(ii) When two normal modes are excited at the natural period of one of them, their responses are in phase quadrature. (approx.)

3. Measurement of Normal Mode Shear Ratios

The shear force ratios for each significant normal mode of a particular shear building are obtained from voltage measurements on the classical inductor capacitor analogue of Fig. 1(b), in which inductance is proportional to floor mass and capacitance is inversely proportional to interstorey stiffness. Currents and voltages correspond to velocities and forces. This analogue is discussed in detail by Murphy, Bycroft and Harrison [3]. The damping should be small but need not be known.

The analogue is excited at a natural period by a current generator applied to the base. The natural period is identified by the phase equality of the base current and voltage. The voltage ratios are measured by a phase sensitive bridge. The low damping ensures that the voltages of the non-resonant normal modes are much smaller than those of the resonant normal mode under examination. The small voltages of these non-resonant modes are discriminated against by the phase sensitive bridge, since they are in phase quadrature with the reference voltage. The measured voltage ratios are equal to the normal mode shear ratios of the building since a change of scale does not alter the normal mode shape.

Although the building natural periods can be calculated from the shear force ratios, together with the mass and stiffness distributions, it is found more convenient to obtain them by scaling from the measured analogue natural periods.

4. Calculation of Modal Properties - Static Responses

4.1 Modal Shear Force at Resonance - $S_{r,m}$

The actual shear forces in the building normal modes may be calculated from the measured shear force ratios by using the power relationship which defines the damping factor. A simple mechanical resonator, with damping factor n_m, is maintained in steady oscillation by a base acceleration A_b, whose period T_m equals the natural period of the oscillator.

$$\text{Maximum potential energy} = \frac{1}{2n_m}\left(\frac{T_m}{2\pi}\right) \quad \text{input power} \qquad (1)$$

Since a normal mode behaves as a simple resonator [1], we may substitute its parameters in eqn. (1). If the shear force in normal mode m, at floor r, is $S_{r,m}$ and the inter-storey stiffness is k_r,

$$\sum_{i=1}^{N}\frac{1}{2}\left(\frac{1}{12k_i}\right)\left(S_{i,m}\right)^2 = \frac{1}{2n_m}\left(\frac{T_m}{2\pi}\right)\frac{1}{2}\left(\frac{T_m}{2\pi}\right)A_b S_{i,m} \qquad \text{ft-lb}$$

where the input power follows from the phase equality of the base velocity and shear force.

$$\text{Hence} \qquad S_{r,m} = \frac{A_b 12k_1}{2n_m}\left(\frac{T_m}{2\pi}\right)^2 \frac{1}{\sum_{i=1}^{N}\frac{k_1}{k_i}\left(\frac{S_{i,m}}{S_{1,m}}\right)^2}\left(\frac{S_{r,m}}{S_{1,m}}\right) \qquad \text{lb} \qquad (2)$$

4.2.1 Modal Shear Force for Static Acceleration g

If the shear forces of eqn. (2) are divided by the resonant amplification $1/2\, n_m$, and A_b taken equal to g, we obtain the shear forces in normal mode m under a static acceleration g.

$$S'_{r,m} = g(12k_1)\left(\frac{T_m}{2\pi}\right)^2 \frac{1}{\sum_{i=1}^{N}\frac{k_1}{k_i}\left(\frac{S_{im}}{S_{1,m}}\right)^2}\left(\frac{S_{r,m}}{S_{1,m}}\right) \qquad \text{lb} \qquad (3)$$

4.2.2 Modal Bending Moment for Static Acceleration g

The bending moment at floor r may be obtained by summing the moments of the forces exerted by all higher floors. Since the force exerted by a floor equals the change of shear force across it,

$$M'_{r,m} = \sum_{i=r+1}^{N} h(i-r)\left(S'_{i,m} - S'_{i+1,m}\right) \qquad \text{for} \quad h_i = h$$

Hence $$M'_{r,m} = h\sum_{i=r+1}^{N} S'_{i,m} \qquad lb\text{-}ft \qquad (4)$$

4.2.3 Modal Displacement for Static Acceleration g

The displacement at floor r is obtained by summing the displacements below it.

$$x'_{r,m} = \sum_{i=1}^{r} \frac{S'_{i,m}}{12 k_i} \qquad ft \qquad (5)$$

4.3 Static Modal Responses of Standardized Buildings

For convenience of plotting we now express the static normal mode responses of eqns. (3) (4) and (5) in terms of "standardized" buildings. To standardize any building, multiply the floor masses and interstorey stiffnesses by a pair of factors chosen to give a standard first storey,

	standard first floor mass	=	10^6 lb
	standard first floor stiffness	=	10^6 lb/in
Also	standard first floor height	=	10 ft

4.3.1 Standardized Static Shear Force $\bar{S}_{r,m}$

$$S'_{r,m} = \frac{m_1}{10^6}\,\bar{S}_{r,m} \qquad \text{lb} \qquad (6)$$

where $$\bar{S}_{r,m} = 12g\,10^6\left(\frac{\bar{T}_m}{2\pi}\right)^2 \frac{1}{\sum_{i=1}^{N} \frac{k_1}{k_i}\left(\frac{S_{i,m}}{S_{1,m}}\right)^2}\left(\frac{S_{r,m}}{S_{1,m}}\right) \qquad \text{lb} \qquad (7)$$

and $$\bar{T}_m^2 = \frac{k_1}{m_1}\,T_m^2 \qquad \text{sec} \qquad (8)$$

4.3.2 Standardized Static Bending Moment $\overline{M}_{r,m}$

$$M'_{r,m} = \left(\frac{m_1}{10^6}\right)\left(\frac{h}{10}\right)\overline{M}_{r,m} \qquad \text{lb-ft} \qquad (9)$$

where $$\overline{M}_{r,m} = 10 \cdot \sum_{i=r+1}^{N} \overline{S}_{i,m} \qquad \text{lb-ft} \qquad (10)$$

4.3.3 Standardized Static Displacement $\overline{X}_{r,m}$

$$X'_{r,m} = \left(\frac{m_1}{10^6}\right)\left(\frac{10^6}{k_1}\right)\overline{X}_{r,m} \qquad \text{in.} \qquad (11)$$

$$\overline{X}_{r,m} = 10^{-6}\sum_{i=1}^{r}\frac{k_1}{k_i}\overline{S}_{i,m} \qquad \text{in.} \qquad (12)$$

4.4 Modal Responses for 10-Storey Standardized Buildings

A number of standardized mass and stiffness distributions for 10-storey buildings are defined in Fig. (2). Taken in pairs, these define standardized buildings, each of which is set up on the electrical analogue described in section 3. The shear force ratios and natural periods of the building normal modes are measured. These ratios and periods are substituted in eqns. (7) (10) and (12) to obtain the responses of the normal modes of the standardized buildings to a static acceleration g. Some of these responses and natural periods are given in Figs. (3) to (13). It should be noted that interpolation gives responses for mass and stiffness distributions between those defined in Fig. (2). The rapid fall of response amplitude with mode number is also evident.

The responses of buildings with non-standard first storeys may be obtained from the above, using eqns. (6), (8), (9) and (11).

4.5 Buildings of N storeys

A building of N storeys may be applied to the mass and stiffness distributions of Fig. (2). It is first reduced to an equivalent 10-storey building.

Multiply floor numbers by $\frac{10}{N}$

Multiply floor masses by $\frac{N}{10}$

Multiply interstorey stiffness by $\frac{10}{N}$

Multiply interstorey height by $\frac{N}{10}$

We thus obtain the masses m_r and stiffnesses k_r at N (generally) non-integral floor numbers.

This equivalent 10-storey building is next standardized in accordance with section 4.3 and may then be applied to a chart of the type given in Fig. (2).

Particular floors may be eliminated (approximately) by combining masses and flexibilities. Unequal storey heights may be treated, but the discussion is omitted owing to space limitations.

4.6 Accuracy and Checking

Straightforward measuring techniques keep the overall errors in the determination of the normal mode properties down to about 1%. A very effective overall check on both the measurements and the calculations is possible since the static shear force, bending moment, or displacement at any floor is simply equal to the sum of the static responses of all the corresponding normal modes.

5. RESPONSE OF BUILDING NORMAL MODES TO AN EARTHQUAKE

The modal weights and periods at floor r of a shear building are obtained from the appropriate curves of Figs. (3) to (13) together with the eqns. (6), (9) and (11). For buildings of other than 10 storeys the factors of section 4.5 are applied first.

In order to measure the shear force which would occur at floor r of a building during a particular earthquake, we add simultaneously the shear forces generated in each of the normal modes, using an electrical analogue. The measuring techniques are discussed in "Paper A" [1]. A similar addition of modal responses gives the bending moment or displacement at floor r.

We define a generic term for the responses to a static acceleration g, at floor r, in normal mode m.

$$\mathcal{M}_{r,m} = S'_{r,m} \, , \; M'_{r,m} \; \text{or} \; X'_{r,m} \tag{13}$$

Let R_m be the earthquake response of a resonator of unit weight, natural period T_m, and damping factor n_m. Then the response of a resonator of weight $\mathcal{M}_{r,m}$ is given by

$$\mathcal{R}_{r,m} = R_m \mathcal{M}_{r,m} \tag{14}$$

The maximum earthquake response at floor r is

$$\left[\sum_{i=1}^{N} \mathcal{R}_{i,m} \right]_{max} = \mathcal{M}_{r,1} E\left(1, \frac{\mathcal{M}_{r,2}}{\mathcal{M}_{r,1}}, \ldots, \frac{\mathcal{M}_{r,N}}{\mathcal{M}_{r,1}}\right) \tag{15}$$

where

$$E\left(1 \; \ldots, \frac{\mathcal{M}_{r,N}}{\mathcal{M}_{r,1}}\right) = \left[R_1 + \frac{\mathcal{M}_{r,2}}{\mathcal{M}_{r,1}} R_2 + \cdots + \frac{\mathcal{M}_{r,N}}{\mathcal{M}_{r,1}} R_N \right]_{max}$$

To measure E an electrical analogue is set up with resonators whose static responses, natural periods, and dampings correspond to the building modal static responses, natural periods, and dampings. An electrical equivalent of the earthquake motion is applied to the analogue and the maximum response recorded. An electrical equivalent of a static acceleration g is then applied to the resonator for mode 1 and its response is recorded. The ratio of these two responses is E, in accordance with eqn. (15).

Two resonators were set up and the Taft earthquake applied to obtain E values for the first two normal modes for various natural periods, static responses, and damping factors. Values for E(1,0), E(1,0.3), E(1,0.5) and E(1,-0.5) are given in Figs. (14) to (19). When these E values are multiplied by $\mathcal{M}_{r,1}$ they give, for floor r, the maximum response of the building normal modes 1 and 2 to the Taft Earthquake. An upper limit for the contribution of normal mode 3 is given by the product $\mathcal{M}_{r,3}\,E(1,0)$, where E is the value for period T_3.

6. SHEAR BUILDING RESPONSE TO TAFT EARTHQUAKE: OUTLINE OF PROCEDURE

(a) Obtain the effective floor masses, inter-storey shear stiffnesses, and estimate the normal mode dampings.

(b) Reduce the building to an equivalent building of 10 storeys with the factors of section 4.5. This gives m_r, k_r and h_r, where r may be non-integral.

(c) Reduce this equivalent building to the standard form defined in section 4.3.

(d) Apply the building stiffness distribution obtained in (c) to the curves of Fig. (2a) and the mass distribution to the curves of Fig. (2b). The building type is now defined by a number and letter, e.g., IIC. Interpolation between numbers and letters is permitted.

(e) The static shear force $\bar{S}_{r,m}$ bending moment $\bar{M}_{r,m}$, and displacement $\bar{X}_{r,m}$, and the period $\bar{T}_m$ are obtained for the standardized building from the curves of Figs. (3) to (13), e.g., for floor 3, normal mode 2, building type IIC, $\bar{M}_{3,2} = -20.10^6$ lb-ft and $\bar{T}_2 = 1.06$ sec. from Fig. (10).

(f) The static modal responses and natural periods of the equivalent 10-storey building $S'_{r,m}$, $M'_{r,m}$, $X'_{r,m}$ and T_m, are obtained from eqns. (6), (9), (11) and (8), e.g., for $\bar{M}_{3,2} = -20.10^6$ lb-ft, $\bar{T}_2 = 1.06$ sec, $k_1 = 8.10^6$ lb-in, $m_1 = 2.10^6$ lb, and $h = 8$, then

$$M'_{3,2} = \frac{2.10^6}{10^6}\,\frac{8}{10}\,(-20.10^6) = -32.10^6 \quad \text{lb-ft}$$

$$T_2 = 1.06\sqrt{\frac{2.10^6}{8.10^6}} = 0.53 \quad \text{sec}$$

These static modal responses give $\mathcal{M}_{r,m}$ as defined in eqn. (13).

(g) Values of $E\left(1, \frac{\mathcal{M}_{r,2}}{\mathcal{M}_{r,1}}\right)$ are now obtained from the curves of Figs. (14) to (19).

(h) The building response at floor r for normal modes 1 and 2 is now

$$\left[\mathcal{R}_{r,1} + \mathcal{R}_{r,2}\right]_{max} = \mathcal{M}_{r,1} E\left(1, \frac{\mathcal{M}_{r,2}}{\mathcal{M}_{r,1}}\right)$$

(i) An upper limit to the contribution of normal mode 3 is obtained by adding its response, without regard to sign.

$$\left[\mathcal{R}_{r,3}\right]_{max} = \mathcal{M}_{r,3} E(1, 0)$$

We obtain

$$\left|\left[\mathcal{R}_{r,1} + \mathcal{R}_{r,2}\right]_{max}\right| + \left|\left[\mathcal{R}_{r,3}\right]_{max}\right|$$

7. WORKED EXAMPLE

An 8-storey shear building has been designed with the floor masses and inter-storey shear stiffnesses listed below. The damping factors of normal modes 1, 2 and 3 are estimated as 0.05. The inter-storey height is 9 feet. The designer wishes to find the shear force which the Taft earthquake would have generated at floor 4.

Designed Building			Equivalent 10-Storey Building			Standardized Building		
Storey No.	Mass lb	Stiff-ness lb/in	Storey No. r	Mass m_r-lb	Stiff-ness k_r - lb/in	Storey No. r	Mass lb	Stiff-ness lb/in
8	1.10^6	1.10^6	10.0	$0.8.10^6$	$1.25.10^6$	10.0	$0.5.10^6$	$0.25.10^6$
7	1	1	8.75	0.8	1.25	8.75	0.5	0.25
6	1	1	7.5	0.8	1.25	7.5	0.5	0.25
5	1	1	6.25	0.8	1.25	6.25	0.5	0.25
4	2	4	5.0	1.6	5	5.0	1	1
3	2	4	3.75	1.6	5	3.75	1	1
2	2	4	2.5	1.6	5	2.5	1	1
1	2	4	1.25	1.6	5	1.25	1	1
						1	1	1

The procedure outlined in section 6 is followed:-

(6(b)) - The designed building is reduced to the equivalent 10-storey building as given above. This defines the masses m_r and stiffnesses k_r. Notice that storey 4 has become the equivalent storey 5. The equivalent inter-storey height becomes

$$h = 9\frac{8}{10} = 7.2 \text{ ft}$$

(6(c)) - The equivalent 10-storey building is reduced to the standardized building, also given above.

(6(d)) - The standardized storey numbers give the ordinates, and the standardized masses and stiffnesses give the abscissae to be sketched on the charts of Figs. 2(a) and 2(b). It is seen that the building is of type VE.

(6(e)) - The static modal shear force and the natural periods of the standardized building, at the equivalent floor 5, are obtained from Fig. (7),

$$\bar{S}_{5,1} = 3{\cdot}72.10^6 \;,\; \bar{S}_{5,2} = 0{\cdot}118.10^6 \;,\; \bar{S}_{5,3} = -0{\cdot}24.10^6 \qquad lb$$

$$\bar{T}_1 = 2{\cdot}04 \;,\; \bar{T}_2 = 0{\cdot}953 \;,\; \bar{T}_3 = 0{\cdot}54 \qquad sec$$

(6(f)) - The static modal responses of the equivalent 10-storey building are obtained by comparing its first storey parameters with the fixed first storey parameters of the standardized building.

$$S'_{5,1} = \frac{m_1}{10^6}\frac{h}{10}\bar{S}_{5,1} = \frac{1{\cdot}6.10^6}{10^6}\frac{7{\cdot}2}{10}\,3{\cdot}72.10^6 = 4{\cdot}28.10^6 = \mathcal{M}_{5,1} \qquad lb$$

$$S'_{5,2} = \frac{m_1}{10^6}\frac{h}{10}\bar{S}_{5,2} = \frac{1{\cdot}6.10^6}{10^6}\frac{7{\cdot}2}{10}\,0{\cdot}118.10^6 = 0{\cdot}136.10^6 = \mathcal{M}_{5,2} \qquad lb$$

$$S'_{5,3} = \frac{m_1}{10^6}\frac{h}{10}\bar{S}_{5,3} = \frac{1{\cdot}6.10^6}{10^6}\frac{7{\cdot}2}{10^6}(-0{\cdot}24.10^6) = -0{\cdot}276.10^6 = \mathcal{M}_{5,3} \qquad lb$$

$$T_1 = \bar{T}_1\sqrt{\frac{m_1}{k_1}} = 2{\cdot}04\sqrt{\frac{1{\cdot}6}{5}} = 1{\cdot}15 \qquad sec$$

$$T_2 = \bar{T}_2\sqrt{\frac{m_1}{k_1}} = 0{\cdot}953\sqrt{\frac{1{\cdot}6}{5}} = 0{\cdot}539 \qquad sec$$

$$T_3 = \bar{T}_3\sqrt{\frac{m_1}{k_1}} = 0{\cdot}54\sqrt{\frac{1{\cdot}6}{5}} = 0{\cdot}305 \qquad sec$$

(6(g)) - $E\left(1, \frac{\mathcal{M}_{5,2}}{\mathcal{M}_{5,1}}\right) = E\left(1, \frac{0{\cdot}136}{4{\cdot}28}\right) \qquad = E(1, 0{\cdot}032)$

The curves for E(1, 0.032) and for T_1/T_2 = 2.14 are given approximately in Fig. (15a). T_1 = 2.04, E(1, 0.032) = 0.082.

(6(h)) - $[\mathcal{R}_{5,1} + \mathcal{R}_{5,2}]_{max} = \mathcal{M}_{5,1} E(1, 0{\cdot}032)$

$$= 4{\cdot}28.10^6 . 0{\cdot}082 \qquad = 0{\cdot}35.10^6 \quad lb$$

(6(i)) - $[\mathcal{R}_{5,3}]_{max} = \mathcal{M}_{5,3} E(1, 0)$

$$= -0{\cdot}276.10^6 . 0{\cdot}37 \qquad = -0{\cdot}102.10^6 \quad lb$$

Where E(1, 0) is obtained from Fig. (15a) for the period T_3 = 0.540 sec.

An upper limit for the shear force generated by the Taft earthquake at the equivalent floor 5, or floor 4 of the designed building, is

$$0{\cdot}35.10^6 + 0{\cdot}102.10^6 \quad = \quad 0{\cdot}452.10^6 \qquad lb$$

8. DISCUSSION

An approximation is used for the contribution of the mode 3 to reduce the number of cases. The over-estimation of the response of the first three normal modes is small if $[\mathcal{R}_{r,3}]_{max}$ is a small fraction of the total response. If the response curves E are eventually obtained as smooth probability curves, by considering a large number of earthquakes, it should be possible to determine what fraction of the probable response of normal mode 3 should be added to the probable response of the first two normal modes.

9. BIBLIOGRAPHY

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2) J.M.S. Rayleigh, Lord, The Theory of Sound. Vol. I Dover Publications, New York (1945), pp 91-169.

9. NOMENCLATURE (See also Paper A[1])

$\bar{X}_{r,m} \quad \bar{S}_{r,m}, \bar{M}_{r,m}$ - displacement (rel. to base), shear force, bending moment, of normal mode m at floor r - in, lb-ft, lb.

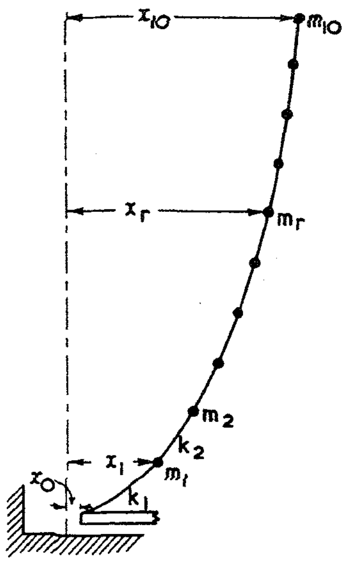

Fig. 1(a) Idealized shear building

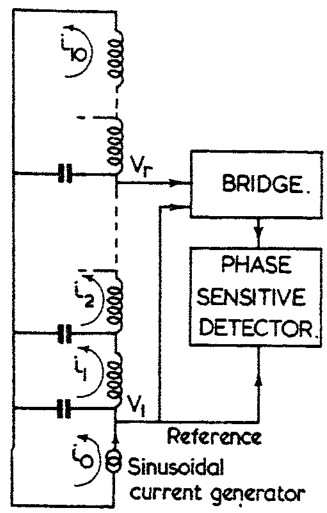

Fig. 1(b) Shear building analogue instrumented to measure shear ratios

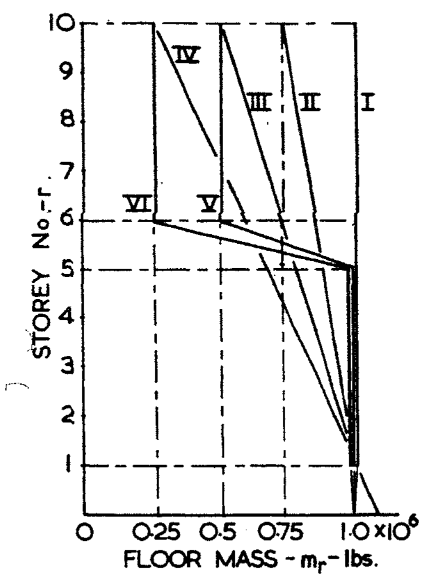

Fig. 2(a) Mass distributions of standard 10-storey building

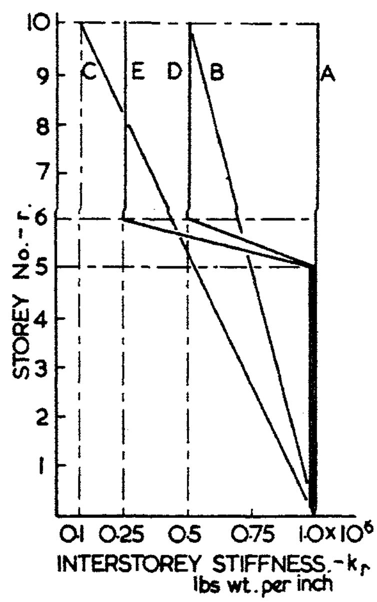

Fig. 2(b) Interstorey stiffness distributions of standard 10-storey buildings.

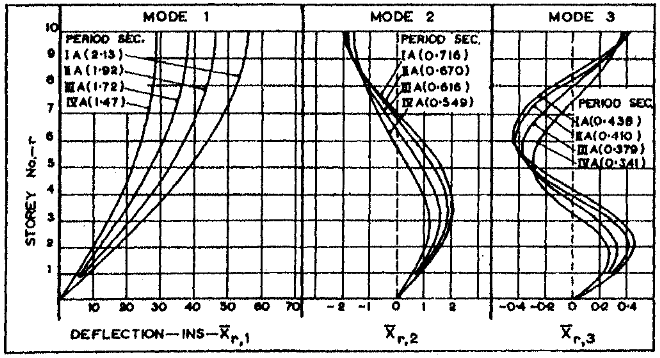

Fig. 11 Static deflections and periods, normal modes 1, 2, 3, standard 10-storey buildings, type IA, IIA, IIIA, IVA.

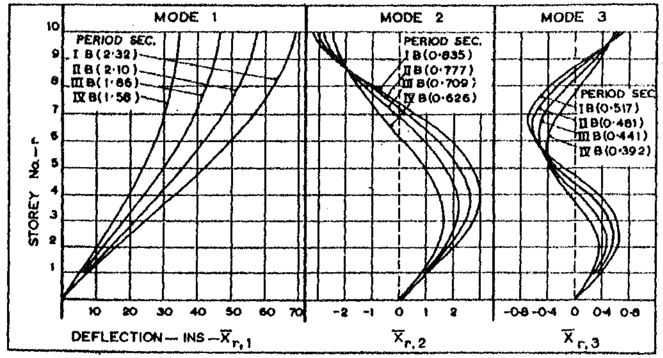

Fig. 12 Static deflections and periods, normal modes 1, 2, 3, standard 10-storey buildings, type IB, IIB, IIIB, IVB.

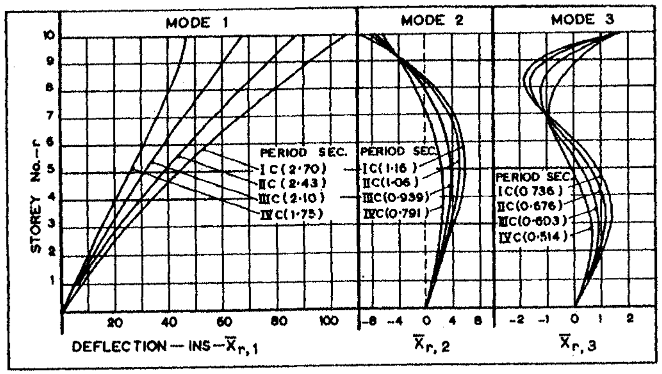

Fig. 13 Static deflections and periods, normal modes 1, 2, 3, standard 10-storey buildings, type IC, IIC, IIIC, IVC.

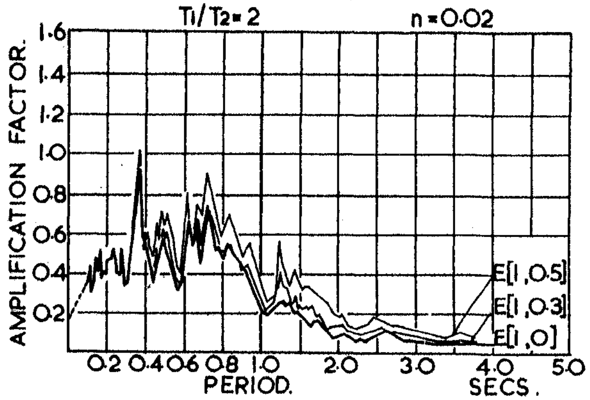

Fig. 14(a) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.02, T_1/T_2 = 2.0

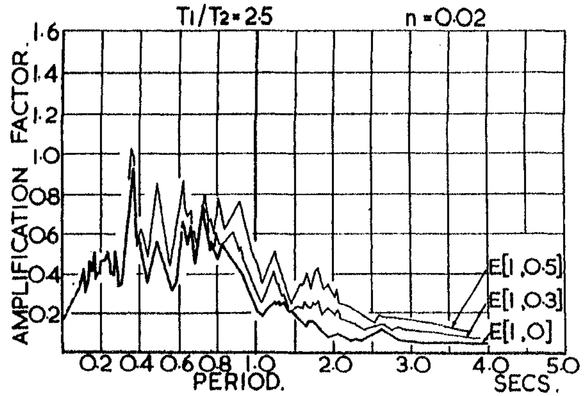

Fig. 14(b) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.02, T_1/T_2 = 2.5

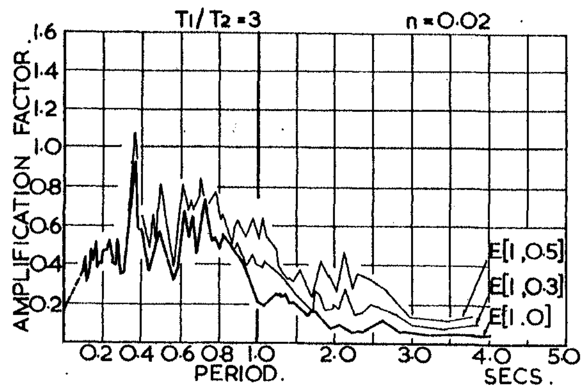

Fig. 14(c) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.02, T_1/T_2 = 3.0

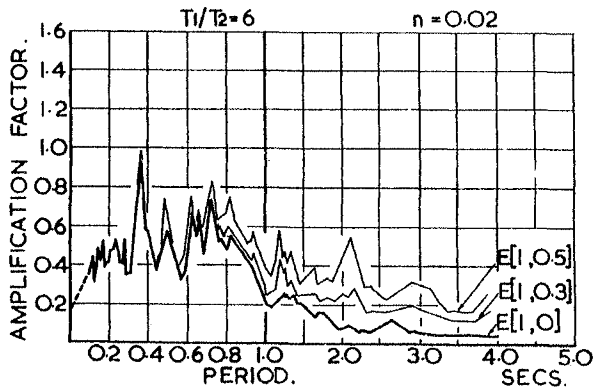

Fig. 14(d) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.02, T_1/T_2 = 6.0

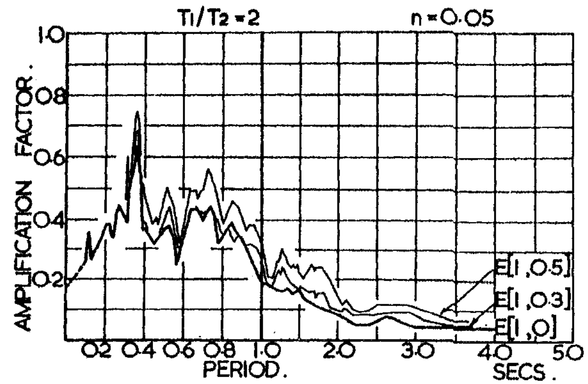

Fig. 15(a) Modal responses to Taft earthquake (*N.21.E, 21.7.1952*) $n = 0.05$, $T_1/T_2 = 2.0$

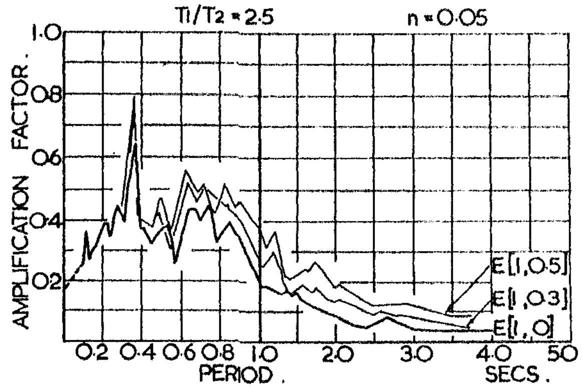

Fig. 15(b) Modal responses to Taft earthquake (*N.21.E, 21.7.1952*) $n = 0.05$, $T_1/T_2 = 2.5$

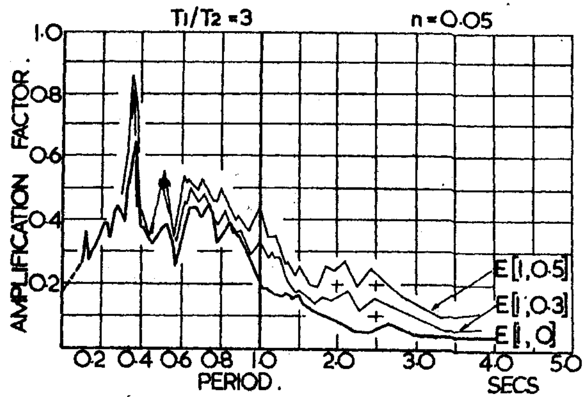

Fig. 15(c) Modal responses to Taft earthquake (N.21.E, 21.7.1952) $n = 0.05$, $T_1/T_2 = 3.0$

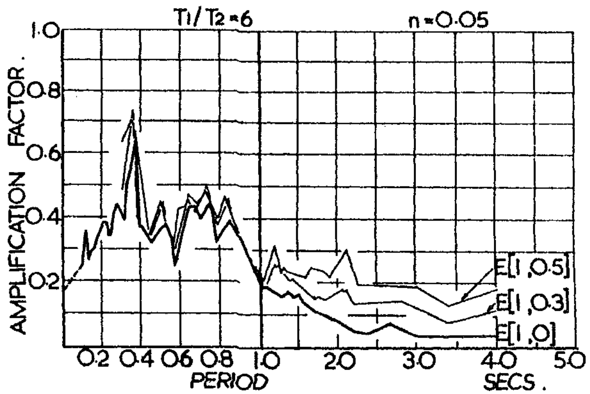

Fig. 15(d) Modal responses to Taft earthquake (N.21.E, 21.7.1952) $n = 0.05$, $T_1/T_2 = 6.0$

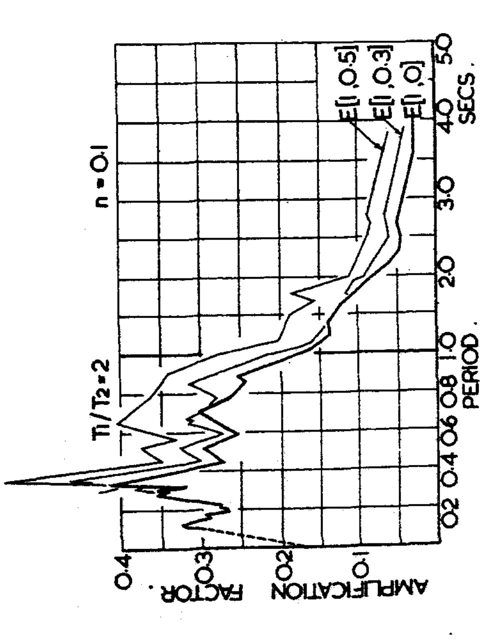

Fig. 16(a) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.1, T_1/T_2 = 2.0

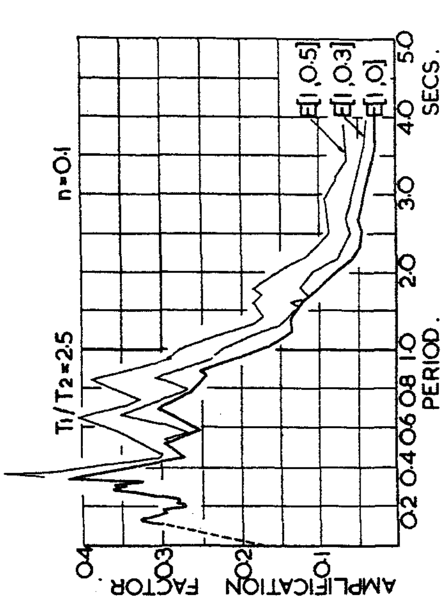

Fig. 16(b) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.1, T_1/T_2 = 2.5

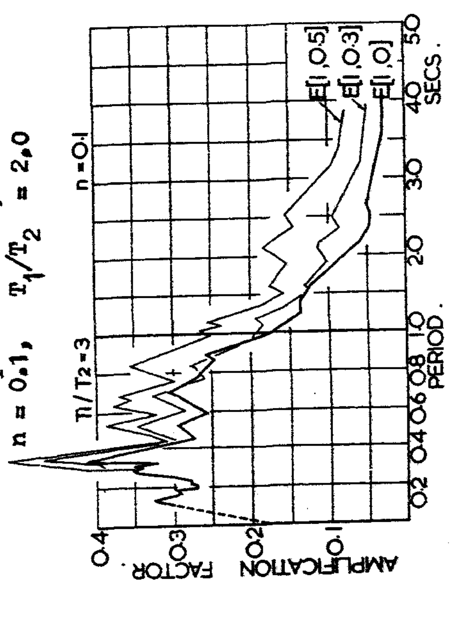

Fig. 16(c) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.1, T_1/T_2 = 3.0

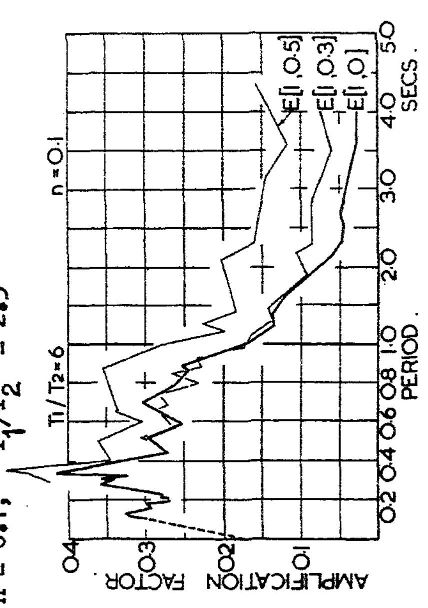

Fig. 16(d) Modal responses to Taft earthquake (N.21.E, 21.7.1952) n = 0.1, T_1/T_2 = 6.0

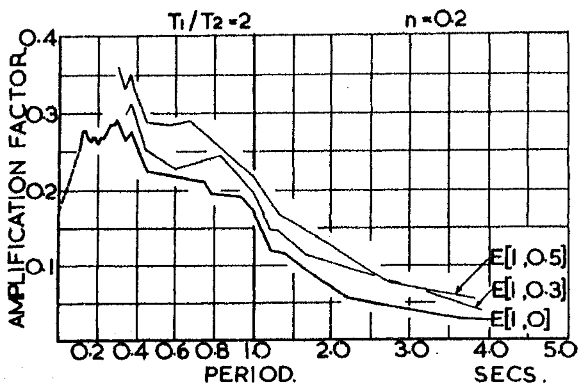

Fig. 17(a) Modal responses to Taft earthquake (N.21.E, 21.7.1952)
$n = 0.2, \quad T_1/T_2 = 2.0$

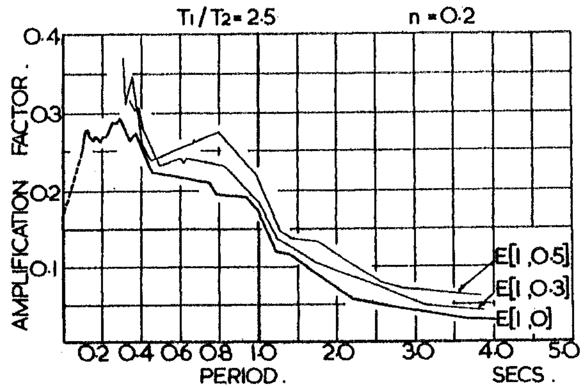

Fig. 17(b) Modal responses to Taft earthquake (N.21.E, 21.7.1952)
$n = 0.2, \quad T_1/T_2 = 2.5$

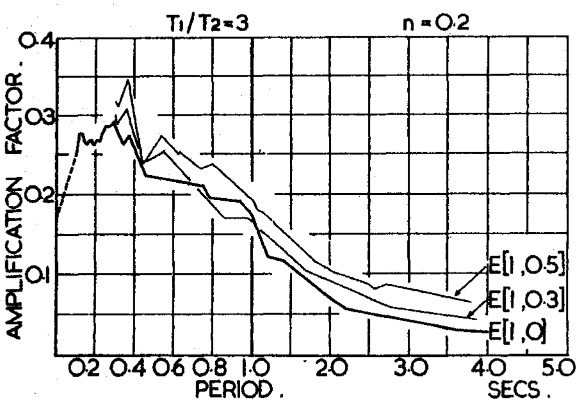

Fig. 17(c) Modal responses to Taft earthquake (N.21.E, 21.7.1952)
$n = 0.2, \quad T_1/T_2 = 3.0$

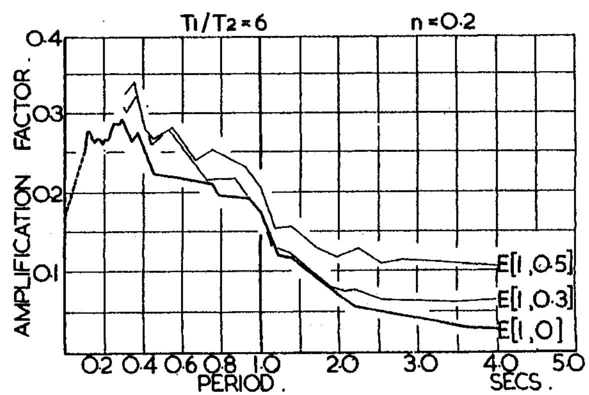

Fig. 17(d) Modal responses to Taft earthquake (N.21.E, 21.7.1952)
$n = 0.2, \quad T_1/T_2 = 6.0$

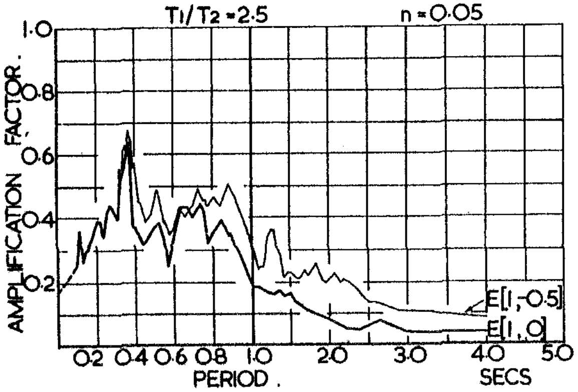

Fig. 18(a) Modal responses to Taft earthquake, second mode negative, $n = 0.05$, $T_1/T_2 = 2.5$

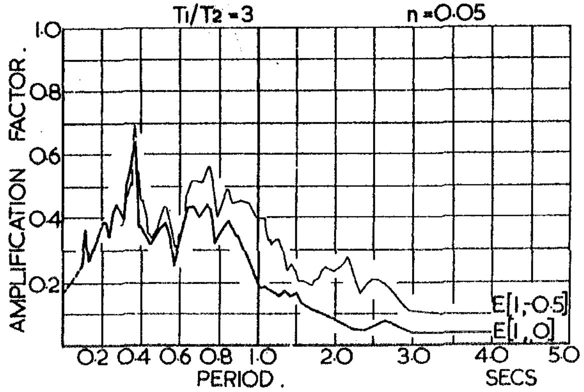

Fig. 18(b) Modal responses to Taft earthquake, second mode negative, $n = 0.05$, $T_1/T_2 = 3.0$

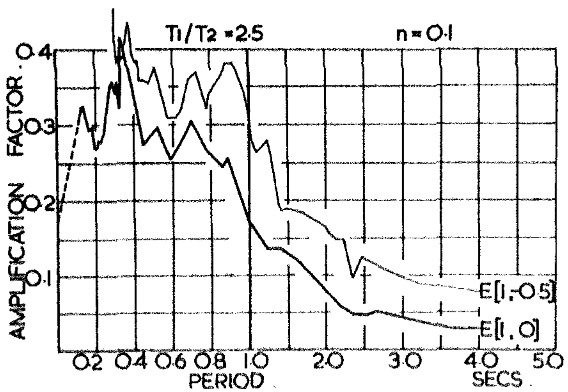

Fig. 19(a) Modal responses to Taft earthquake, second mode negative, $n = 0.1$, $T_1/T_2 = 2.5$

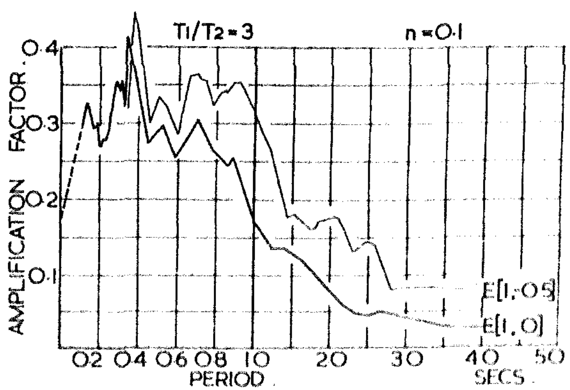

Fig. 19(b) Modal responses to Taft earthquake, second mode negative, $n = 0.1$, $T_1/T_2 = 3.0$