SEISMIC WALL EFFECT IN FRAMED STRUCTURE IN RELATION TO THE PERIOD OF TALL BUILDINGS

by

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Introduction

At the 1923 Kanto earthquake the author investigated the damages of buildings in Tokyo and Yokohama districts and found that the damages of tall buildings are not independent of the natural period of building. The author has proposed the following formula $T = 0.07N \sim 0.09N$ sec. to determine the soundness of a building by the period T in relation to the number of stories N of the building. Observations of the natural period of buildings were attempted to a limited degree in connection with the repair work of the buildings that had been damaged by the earthquake. In 1929 the author also made similar observations during the repairwork of the Yurakukan building of 8 storied steel construction, which was severely damaged at Kanto earthquake. The author designed the increasing of the rigidity of the building by the setting of the new seismic wall and managed the execution and proved that the period of the building decreased from 0.8 sec. to 0.5 sec. by continuous observations through the period of the repair work.

Before the war there were not so many examples to prove whether the author's criteria are real or not, but after the war the author was informed that more than 3,000 vibration observations had been made by the United States Coast and Geodetic Survey, and that the Joint Committee on Lateral Force of Earthquake and Wind in San Francisco proposed the new formula $T = 0.05H/\sqrt{D}$ sec. for the criterion of soundness. This is quite different from the author's formula. Then the author's formula must be confirmed by those many observations in U.S.A., and by the observations on Japanese buildings which have been built after the Kanto earthquake.

After the Kanto earthquake Japanese architects had been taught that a curtain wall system should not be used, and that to resist the seismic force as severe as Kanto earthquake it was necessary to use the rigidly connected steel skelton with reinforced concrete walls. But how much rigidity of the wall should be expected with respect to the thickness, height and length, and the opening of the wall and how much seismic coefficients should be used for designing of such a rigid building? Unfortunately the question is not yet solved, and consequently some buildings were constructed to be too weak and others too strong against the same required seismic intensity. Then we wish

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to know how much rigidity or how much period of the building should be required to resist safely and economically the required seismic intensity. This paper is one of the studies which were done over many year to attempt to solve such a problem in the author's laboratory.

Properties of the Building Vibrations.

If the building had no rigid wall, the mode of its vibration would be shear beam type, but if the effective seismic walls were used, the vibration mode would be not only shearing but also bending beam type. Period of shearing vibration is linearly proportional to the total height of structure, but the period of bending vibration is proportional to the square of total height of structure.

The mode of vibration of actual buildings is between shearing and bending. The period of vibration of such a structure can be calculated by the formula (1), which was derived theoretically by the author:

$$T_X = 4\left(e\,\frac{F}{Q}\right)^{\frac{1-m}{2}} H^m \left(\frac{\rho}{g}\right)^{\frac{1}{2}} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where suffix X of T_X is equal to F/QH^2, F is the constant which shows the rigity of bending, and Q is the constant which shows the rigity of shearing vibration. H is the total height of the structure, and m is index number which varies from 2 to 1 with respect to the bending vibration to shearing, and e is a number which varies corresponding to the mode of bending vibration to shearing vibration. If T_B and T_S denote the periods of bending and shearing vibration, respectively, the value of formula (1) will be identical to the T_B and T_S, respectively, as follows:

$$T_B = 4\left(5\cdot 20H^2\right)^{\frac{1-2}{2}} H^2 \left(\frac{\rho}{g}\right)^{\frac{1}{2}} = 0.4H\sqrt{\frac{\rho}{g}} = 1.787H^2\sqrt{\frac{\rho}{F}}$$

$$T_S = 4\left(e\cdot 0.002H^2\right)^{\frac{1-1}{2}} H^1 \left(\frac{\rho}{g}\right)^{\frac{1}{2}} = 4H\sqrt{\frac{\rho}{g}}$$

To apply the formula (1) to calculate the period of N storied building whose mean height of one story is h, the value of H can be put equal to (N + 0.5)h. What value of X is suitable for the existing buildings? The question is not simple. The author has applied the trial and error method and has taken several values of X from 20 to 0.002. Also what values of h and $\sqrt{\rho/g}$ are suitable for the existing building? The value of h has been taken about 410 cm, which is the mean height of a story of tall buildings in U.S.A., whose periods were observed and total height of building H and number of stories were reported. The value of $\sqrt{\rho/g}$ had been taken about 1.08×10^{-4} C.G.S. unit with the reason later described.

The period of one-story and one-bay frame can be calculated by the formula (2) below, which was derived by the author in 1925, and which has been verified by many experiments:

$$T_{100} = \frac{\pi h^2}{\sqrt{3}} \sqrt{\frac{\rho A_c}{E J_c}} \cdot C \qquad \cdots\cdots (2)$$

$$C = \sqrt{\frac{66 + 246k + 234k^2 + 1.5\lambda^3\xi}{35(2 + 15k + 18k^2)} + \frac{W}{W_c} \cdot \frac{4 + 12k + 9k^2}{2 + 15k + 18k^2}} \cdots (3)$$

When the sectional area of a column A_c is equal to d^2, the formula (2) can be simplified as $T_{100} = \frac{2\pi h^2}{d} \sqrt{\frac{\rho}{E}} \cdot C$ ..... (4)

On the other hand we know the period of one-story and one-bay frame can be calculated by the formula (5):

$$T_{100} = \phi H \sqrt{\frac{\rho}{Q}} \qquad \cdots\cdots (5)$$

$$H = (N + 0.5)h$$

If we equate formula (4) to (5), the following relation can be obtained:

$$\sqrt{\frac{\rho}{Q}} = \frac{2\pi}{1.5} \frac{hC}{d\phi} \sqrt{\frac{\rho}{E}} \qquad \cdots\cdots (6)$$

If the values of ϕ and h/d are taken as h/d = 16, ϕ = 4 and h/d = 16, ϕ = 0.4, we can put as follows: $h/d\phi = 4$ ..... (7)
Then the formula (6) can be written as formula (8):

$$\sqrt{\frac{\rho}{Q}} = \frac{8\pi C}{15} \sqrt{\frac{\rho}{E}} \qquad \cdots\cdots (8)$$

If the value of C were taken equal to 1.87 which can be calculated by the formula (3) under the condition of k = 1, λ = 1, ξ = 1 and W/W_c = 4, the formula (8) can be written as formula (9):

$$\sqrt{\frac{\rho}{Q}} = 10\pi \sqrt{\frac{\rho}{E}} \qquad \cdots\cdots (9)$$

If the material of the frame is of reinforced concrete we know that the following values are suitable:

$$\sqrt{\frac{\rho}{E}} = 3.4 \times 10^{-6} \quad \text{in C.G.S. unit}$$

$$\sqrt{\frac{\rho}{Q}} = 1.08 \times 10^{-4} \quad " \quad " \quad " \qquad \cdots\cdots (10)$$

Then the formula (1) can be calculated as formula (11) by using the above mentioned values thus we get

$$T_{1.25} = 1.4(N+0.5)h\sqrt{\frac{\rho}{Q}} = 0.062(N+0.5)$$
$$T_{0.75} = 1.7(\ \ )\ \ \ = 0.075(\ \ )$$
$$T_{0.55} = 1.9(\ \ )\ \ \ = 0.084(\ \ )$$
$$T_{0.31} = 2.24(\ \ )\ \ \ = 0.099(\ \ ) \qquad \cdots\cdots (11)$$
$$T_{0.02} = 3.4(\ \ )\ \ \ = 0.15(\ \ )$$

The formula (11) shows the period of the building which can be generaly formulated as follows:

$$T = Z(N+0.5)\ \text{sec.} \qquad \cdots\cdots (12)$$

where N is the number of stories of building. When N is large compared to 0.5, 0.5 may be neglected and the period of buildings can be easily calculated by formula (13):

$$T = ZN\ \text{sec.} \qquad \cdots\cdots (13)$$

The value of Z is simple numbers such as 0.07, 0.08 and so on in ordinary buildings.

Periods of Existings Buildings

Figure 1 shows the relation of the formula (12) and the period of many existing buildings which were observed by U.S. Coast and Geodetic Survey, and which were reported by Franklin P. Ulrich and Deans Carder in Proceedings of the Symposium on Blast Effects on Structure, 1952. As the original report shows the relation of total height of building to the period, the author assumed that the mean height of one story is about 410 cm by the reason already described. The center line on these graphs represents nearly average trend of periods drawn by the original reporter, and this trend is just identical to that given by the author's formula 0.08N sec., and the periods of existing buildings are distributed from 0.035(N + 0.5) sec. to 0.17(N + 0.5) sec.

Figure 2 is another example which shows the same relation between the author's formula and the period of existing buildings some of which are of Japanese buildings and others of tall building in San Francisco, whose number of stories and total height had been reported. The author could assume the mean height of one story of tall buildings in U.S.A. by these data. The periods of Japanese buildings were the values which had been obtained by many observers at early ages associated with Prof. Omori, Prof. Suehiro and Prof. Ishimoto, and at recent time, with Prof. Naito, Dr. Kanai, Mr. Nakagawa, and also by the members of the present author's laboratory. These two figures also illustrate the values of Z which have wide variations in existing buildings. Z is a number which corresponds to the rigidity of buildings. Why do wide variations of the rigidity of existing similar storied

building exist? The answer is not simple, but it is evident that the adopted seismic coefficients are not equal in different countries, and if required seismic coefficients were equal, different structural engineers would have different ideas of the total rigidity of buildings, and many engineers would have little knowledge of the quantitative aspect of the effect of walls in the building frame.

Experiments in Laboratory

The author attempted to find the relation between Z and the rigidity of buildings. To find the wall effects on the period of frame the author has tried the model experiments in laboratory. The test pieces were made of hard rubber and its dimensions were designed to be about one hundredth of existing buildings as shown in Fig. 3, and the number of stories N of the test piece were from one to ten, and the number of bays S of the test piece were one to six, and the percentage of window opening area ω to gross area of wall is about 0, 25, 50, 75, and 100. The method of experiment was as follows: The each floor had been sucessively clamped and the clamped level had been changed step by step downward from the nineth floor level to the first floor level, and free vibration periods of the frame that is above clamped level, were observed respectively by the optical method.

The ratio of the period of test piece T_o to the period of the existing building T_e is 100 by scale effect, 1/12.6 by material effect, and 1.3 by load effect; in this case the resulting value is 10.4 which is calculated as follows:

$$\frac{T_e}{T_o} = 100\sqrt{\frac{\rho_e}{\rho_o}\frac{E_o}{E_e}}\cdot\frac{C_e}{C_o} = 100\sqrt{\frac{2.4}{1.4}\cdot\frac{7.5\times10^5}{21.0\times10^7}}\cdot\frac{1.87}{1.43} \approx 10.4 \quad \cdots (14)$$

Then the period of existing building can be said about ten times as great as each value of the test pieces. As the experiments were not easy, the expected acculate results were not obtained, but trend of changing of the period by wall conditions ω, number of stories N and number of bays S and rigidity ratio of wall to the frame can be found exactly. From these results we may derive the following interesting properties:

(1) When the rigidity of columns and beams of the frame were gradually increased from the top floor to the base floor, the rate of increase of the period due to increasing of number of stories is not linearly related to the number of stories N. In ordinary Japanese building frames the mean rigity ratio of the upper story column to the lower story column is about 0.7 or 0.8, the period of N storied frame increases according to N^q, where the value of q is about 0.75~0.85.

(2) In one-bay and N storied frame whose panel is filled up with the wall, the rate of increase of the period due to the number of stories N is proportional to N^m whose value of m increases with the percentage of the opening of wall and the thickness of wall, and in case of a wall with no opening having ordinary thickness, the value

of m increases to about 1.35.

(3) In one-story and S-bay frames whose panel is filled up with the wall, the period changes slightly with the number of bays.

(4) For a walled multi-story frame, the period has a progressively decreasing rate of increase with respect to the number of bays.

A New Formula of the Period of Buildings

By the suggestions of the above described properties in connection with the period of the frame which have been found in the experiments, the author wishes to propose a new formula to calculate the period of the frame with wall:

$$ {}_{NS}T_{\omega} = \Psi_{\omega} \cdot N^{m} \cdot S^{\frac{1-p}{2}} \cdot \Lambda^{\frac{n-q}{2}} \quad \cdots\cdots (15) $$

$$ \Psi_{\omega} = \frac{2\pi h^2}{d}\sqrt{\frac{\rho}{E}} \cdot C \cdot 10^{\left(\frac{\omega-100}{200}\right)\log_{9}(1+D_{0})} \quad \cdots\cdots (16) $$

$$ \Lambda = \frac{1+2n\frac{S^2\lambda^2}{N^2}}{1+2nS^2\lambda^2} \quad \cdots\cdots (17) $$

The symbol ${}_{NS}T_{\omega}$ denotes the period of the frame which is N storied with S bays, and which has the wall opening percentage ω. C is the value which can be calculated by formula (3). D_0 is the shear distribution coefficient of wall and can be calculated by the formula (18):

$$ D_0 = \frac{\gamma[\beta(3\gamma+3)-\alpha(\sqrt{9}\gamma+3)]}{3(3\gamma+3)-(2+n\lambda^2)(\sqrt{9}\gamma+6)} \quad \cdots\cdots (18) $$

$$ D_0 = \frac{P_W}{P_R}, \quad P_R = \frac{P}{1+D_0} \quad \text{and} \quad P_W = \frac{D_0 P}{1+D_0} \quad \cdots\cdots (19) $$

P is the total shearing force acted onto the frame with wall, and P_W is shearing force distributed in the wall only and P_R is shearing force distributed to the surrounding frame only, where

$$ \alpha = \frac{2k+(1+\frac{3}{2}k)\frac{l^2}{d^2}}{2k+(1+6k)\frac{l^2}{d^2}}, \quad \beta = \frac{3k}{2k+(1+6k)\frac{l^2}{d^2}}, \quad \sqrt{9} = \frac{1+6k}{2k+(1+6k)\frac{l^2}{d^2}} \quad \cdots (20) $$

$$ k = \frac{J_B}{J_C}\cdot\frac{h}{l}, \quad \gamma = \frac{J_W}{J_C} = \frac{tl^3}{bd^3} \quad \text{and} \quad \lambda = \frac{l}{h} \quad \cdots\cdots (21) $$

$$ n = \frac{KE}{2G} \quad \cdots\cdots (22) $$

The formula (18) had been derived by the author theoretically to calculate the shear distribution coefficient D_0 in the case shown in Fig. 5 under the conditions of the equal horizontal and vertical displacements of the four corners of the wall and the frame, when the total shearing force P acts onto the frames. The formula (18) is very complex, but for practical uses can be simplified as formula (23):

$$D_0 = \frac{\gamma}{A + B n \lambda^2} \qquad \cdots\cdots (23)$$

where $$A = 2\left[1 - \frac{9}{(2+3k)\left(\frac{tl}{bd}+6\right)}\right] \qquad \cdots\cdots (24)$$

$$B = \frac{1+6k}{1+\frac{3}{2}k} \qquad \cdots\cdots (25)$$

For existing building frame, the value of tl/bd can practically be assumed to be 3, when the formula (24) can be simplified as follows:

$$A = 2\left[1 - \frac{1}{2+3k}\right] \qquad \cdots\cdots (26)$$

And thus for practical uses we can put $k = \infty$ and $n = 1.75$; the formula (23) can be simplified as follows:

$$D_0 = \frac{\gamma}{2(1+3.5\lambda^2)} \qquad \cdots\cdots (27)$$

The formula (27) was derived by the author in 1930 and verified to be identical to the experimental results nearly at the stage of the first occurrence of shear hair crack in the reinforced concrete wall.

Period of a Frame with Wall

To calculate the period of the one-story and one-bay frame, the formula (15) can be simplified as follows:

$$_{11}T_\omega = \Psi_\omega \qquad \cdots\cdots (28)$$

That is to say, the function Ψ_ω shows the period of one-story and one-bay frame with wall whose opening is ω percent.

To calculate the period of such a frame the author applied the following interesting properties which have been found by the experiments in the author's laboratory. Fig. 6 shows some results of the experiments. These results teach us that there exists a simple relation in the period of the frame with wall which can be shown as formula (29):

$$\frac{\log \frac{{}_{11}T_{100}}{{}_{11}T_{80}}}{100-80} = \frac{\log \frac{{}_{11}T_{100}}{{}_{11}T_{70}}}{100-70} = \cdots\cdots = \frac{\log \frac{{}_{11}T_{100}}{{}_{11}T_{0}}}{100} = \frac{\log\sqrt{1+D_0}}{100} \qquad \cdots (29)$$

The symbol ${}_{11}T_{100}$ denotes the period of one-story and one-bay frame with 100 percentage opening wall (no wall), and ${}_{11}T_0$ denotes the period of one-story and one-bay frame with 0 percentage opening wall (full wall). By use of the formula (29), the function Ψ_ω can be derived as follows:

$$\log \frac{{}_{11}T_{100}}{{}_{11}T_{\omega}} = \frac{100-\omega}{100}\log\sqrt{1+D_0} \qquad {}_{11}T_\omega = {}_{11}T_{100}\cdot 10^{-\left(\frac{100-\omega}{100}\right)\log\sqrt{1+D_0}}$$

$$\Psi_\omega = {}_{11}T_{100}\cdot 10^{-\left(\frac{100-\omega}{100}\right)\log\sqrt{1+D_0}} \qquad \cdots\cdots (30)$$

The value of $\Psi_\omega / {}_{11}T_{100}$ can be shown in Fig. 10. The value of T_{100} can be calculated easily by using the graph of C with respect to k and W/W_c which are shown in Fig. 11.

Period of One-Story and S-Bay Frame with Wall

The period of one-story and S-bay frame with wall ${}_{1S}T_{\omega}$ can be calculated as follows:

$$ {}_{1S}T_{\omega} \propto \left(\frac{W}{Wc}\cdot\frac{S}{S+1}\right)^{0.5}\cdot\left({}_{11}\Delta_{\omega}\frac{S^{p}}{S+1}\right)^{-0.5} $$

$$ {}_{1S}T_{\omega} \propto \left(\frac{W}{Wc}\right)^{0.5}\cdot{}_{11}\Delta_{\omega}^{-0.5}\,S^{\frac{1-p}{2}} $$

$$ {}_{1S}T_{\omega} = {}_{11}T_{\omega}\cdot S^{\frac{1-p}{2}} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (31) $$

where the symbol ${}_{11}\Delta_{\omega}$ denotes the relative rigidity of one-story and one-bay frame with the wall which has ω percent opening with respect to the rigidity of a column which is calculated as one half of the rigidity of the surrounding frame. The symbol ${}_{1S}\Delta_{\omega}$ denotes the relative rigidity of one-story and S-bay frame with uniformly opened walls. ${}_{1S}\Delta_{\omega}$ can be calculated by the formula (32); and the term γ_{ω} in the formula was found by author's experiments and named the coefficient of continuous wall by the author in 1950

$$ {}_{1S}\Delta_{\omega} = 2SD_{\omega}\gamma_{\omega} + S + 1 \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (32) $$

where D_{ω} denotes the shear distribution coefficient of the wall, or the relative rigidity of a wall which has ω percent opening, with respects to one-story and one-bay frame. Figure 7 shows one example of the value of γ_{ω}, which is a function of t/b and l/h of the wall. Figure 8 shows the relations of ${}_{1S}\Delta_{\omega}$ to ω which can be calculated by formula (32). This graph seems to show that there exists a simple relation between ${}_{1S}\Delta_{\omega}$ and ω, but the author would rather ascert that there exist the simplified relations which can be assumed for practical uses, and which were verified by the author's experiments.

In this example the value of D_{ω} is about 44, which can be calculated by the formula (23) using the following dimensions of the frame with wall. Thickness of wall t = 18 cm, sectional area of a column d^2 = 41 cm^2, height of wall h = 410 cm, λ = 1, k = 1 and n = 1.75. Figure 9 shows one example of the relation of ${}_{11}\Delta_{\omega}$ to ${}_{1S}\Delta_{\omega}$, which can be calculated by the formula (33) practically.

$$ {}_{1S}\Delta_{\omega} = {}_{11}\Delta_{\omega}\,S^{p} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (33) $$

Values of p can be taken as follows with respect to the opening percentages of the wall.

ω	100	80	60	40	20	0
p	0.75	0.85	1.0	1.12	1.18	1.22

By the formula (33) and the value of p with respect to ω, the period of S-bay and one-story frame decreases when $\omega < 60$, but increases when $\omega > 60$, and when $\omega = 60$ the period remains constant regardless of the number of bays of the frame, as shown in Fig. 12. When the value of S tends to ∞, the value of p tends to 1 regardless of the value of ω;

it means that the γ_ω tends to a constant value corresponding to ω when the value of S tends to ∞, and it illustrates that the period of the frame with wall tends to a constant value corresponding to ω.

Value of m and q in N^m and $\Lambda^{\frac{m-q}{2}}$

The letter m is the index number which show the rate of increase of the periods due to increasing of number of stories N corresponding to the degree of combined shearing and bending vibration of N storied frame, as shown in Fig. 4., and q is a function of rigidity ratio of the upper story column and beam to the lower story column and beam of the N storied frame with no wall. When the value of rigidity ratio of column r is equal to 1 and k = 1, then the value of q is equal to 1, and if the value of r is equal to 0.7 or 0.8 as in Japanese ordinary buildings, the value of q is about 0.75 which has been found by the experiments as shown in Fig. 4. The value m is a function of t/b and ω, where t is the thickness of wall, b is depth of sectional area of a column of unit frame, and ω is opening percentage of the wall.

In the case of N storied frame whose unit frame has the following conditions, t/b = 1 and r = 1, the value of m is identical to 2 in the case of $\omega = 0$ and m = 1 in the case of $\omega = 100$, and the values of m varies from 2 to 1 corresponding to ω as in the case of vibration changing from bending to shearing as shown in Fig. 13. When r = 0.8 and q = 0.75 and in the case of $\omega = 100$, the value of m must be equal to 0.75 and at such a frame, the value of m must be equal to $2 - 0.25 = 1.75$ in the case of $\omega = 0$. When $t/b < 1$, the value of m must be taken less than 1.75 in the case of $\omega = 0$.

By using the linear relations between $\log_{11}\Delta_\omega$ and ω, and between $_{11}\Delta_\omega$ and t/b, the value of m can be calculated as in Fig. 13. These values of m are identical to the value of m found in experiments as shown in Fig. 4. Figure 14 shows one example of the value of N^m.

Value of $\Lambda^{\frac{m-q}{2}}$

where $$\Lambda = \frac{1 + 2n\frac{S^2\lambda^2}{N^2}}{1 + 2nS^2\lambda^2}$$

The function Λ is valid in the case of $N > 1$, and represents the ratio of the term of $(1 + 2nS^2\lambda^2)$ of one-story S-bay frame to the term of the N-story S-bay frame. The denominator $(1 + 2nS^2\lambda^2)$ consists of two parts in which when bending deformation is taken as 1, shearing deformation becomes $2nS^2\lambda^2$ for one-story and S-bay frame with wall, whose material constant is equal to n. And $\Lambda^{\frac{m-q}{2}}$ shows the rate of increase of the period of N-story and S-bay frames with the wall corresponding to the ratio of the total height and total width of the frame. The value of $\Lambda^{\frac{m-q}{2}}$ is shown as in Fig. 15, when t/b = 1/5, n = 1.75, and q = 0.75. Now we can calculate easily the periods of the buildings by the formula (15) by using graphs such as shown in Fig. 10, Fig. 11, Fig. 12, Fig. 14 and Fig. 15. Figure 16 shows the

results which have been calculated by the formula (15) to compare with the author's experimental results shown in Fig. 4. The values in the two graphs are quite nearly identical. Figure 17, Fig. 18 and Fig. 19 show the results which were calculated by the formula (15) to compare with the distribution of values of the periods of buildings. Figure 19 shows the results which were calculated by the formula (15) to signify the meaning of the line of $Z(N + 0.5)$. By locating the cross points of the line of $Z(N + 0.5)$ and the line of formula (15), the value of Z can be analyzed with respect to the rigidity of the frames.

Conclusion

As the value of the formula (15) may be equal to the formula (12), the value of Z can be calculated as follows:

$$Z = \Psi_\omega \frac{N^m}{N+0.5} \cdot S^{\frac{1-p}{2}} \Lambda^{\frac{m-q}{2}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (34)$$

and $T = Z(N + 0.5)$ sec.

and when N is large compared to 0.5, we have

$$Z = \Psi_\omega N^{m-1} S^{\frac{1-p}{2}} \Lambda^{\frac{m-q}{2}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (35)$$

and $T = Z N$ sec.

As the values of Z take such simple numbers as 0.07, 0.08 and so on in ordinary existing tall buildings, the author wishes to call Z the "Rigidity Number of Buildings" and recommends the use of Z number for an index of the rigidity of a building.

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NOMENCLATURE

A_c	sectional area of column
b	depth of section of column
D_o	shear distribution coefficient of wall with no opening
D_ω	shear distribution coefficient of wall whose openign is ω percent of gross area of wall
d	width of section of column
E	Young's modulus
G	modulus of rigidity
H	total height of structures
h	height of one story
J_W	moment of inertia of section of a wall
J_c	moment of inertia of section of a column
J_b	moment of inertia of a beam
K_c	J_C/h rigidity of a column
K_B	J_B/ℓ rigidity of a beam
K	shear factor of rectangular section
k	K_B/K_C rigidity ratio
ℓ	length of wall
M	mass
N	number of stories
n	elastic constant of wall
${}_{NS}T_\omega$	period of N-story and S-bay frame with wall whose opening percentage is ω to gross area of wall
W	total weight at floor level
W_C	weight of a column
ρ	density of materials
λ	ℓ/h
γ	J_W/J_C
${}_{1S}\Delta_\omega$	relative rigidity of one-story and S-bay frame with wall whose opening is ω percent.
φ_ω	coefficient of continuous wall
Z	Rigidity Number of Buildings

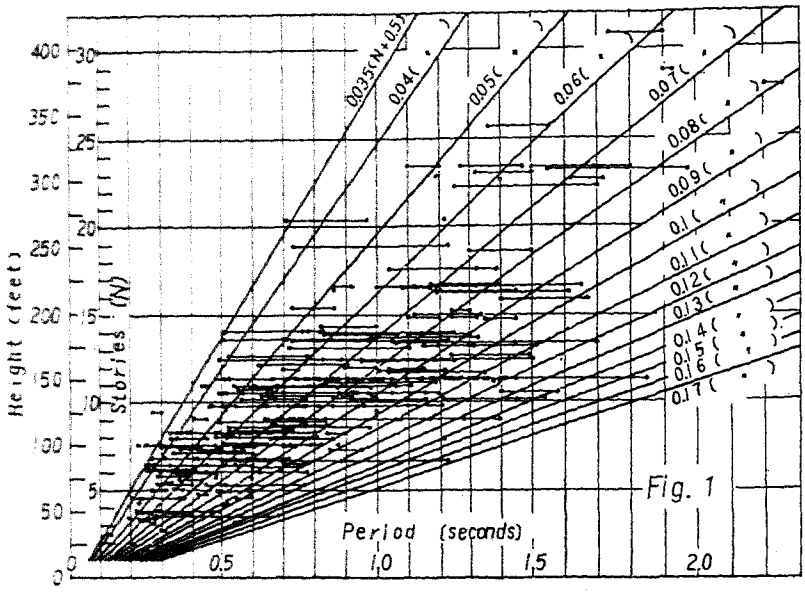
Height (feet)
Stories (N)
0.035(N+0.5)
0.04(
0.05(
0.06(
0.07(
0.08(
0.09(
0.1(
0.11(
0.12(
0.13(
0.14(
0.15(
0.16(
0.17(
Period (seconds)
0.5
1.0
1.5
2.0

Fig. 1

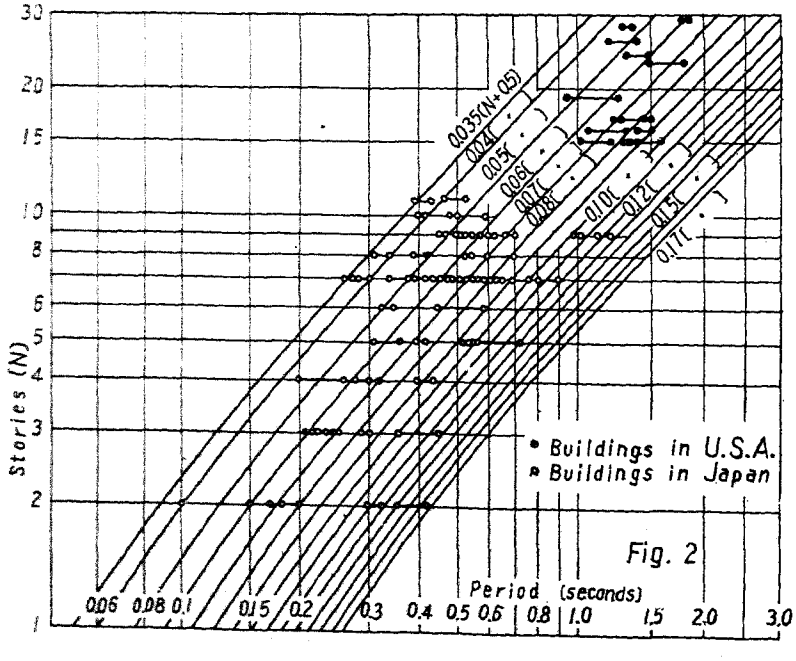
Stories (N)
0.035(N+0.5)
0.04(
0.05(
0.06(
0.07(
0.08(
0.10(
0.12(
0.15(
0.17(
• Buildings in U.S.A.
▫ Buildings in Japan
Period (seconds)
0.06
0.08
0.1
0.15
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.5
2.0
3.0

Fig. 2

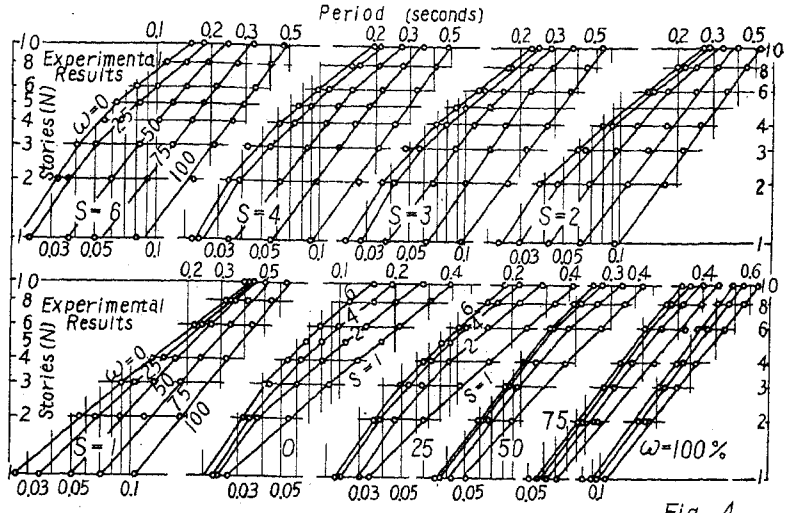

Fig. 4

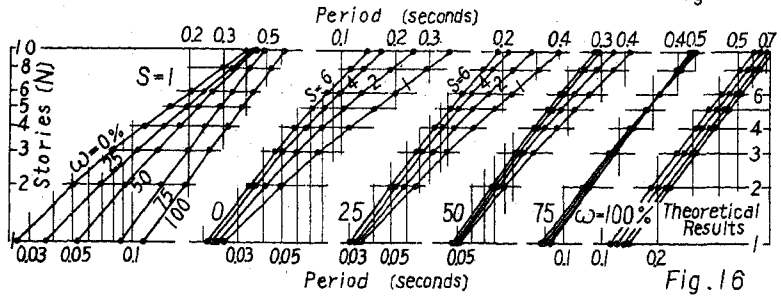

Fig. 16

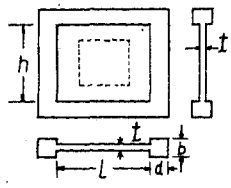

Fig. 5

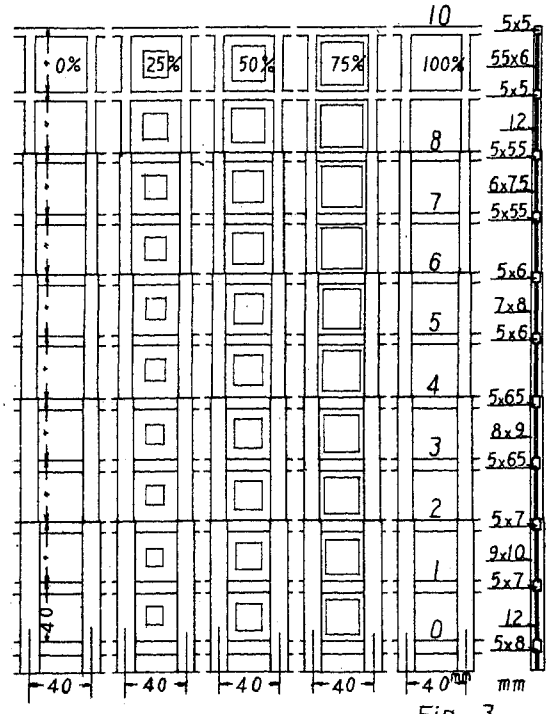

Fig. 3

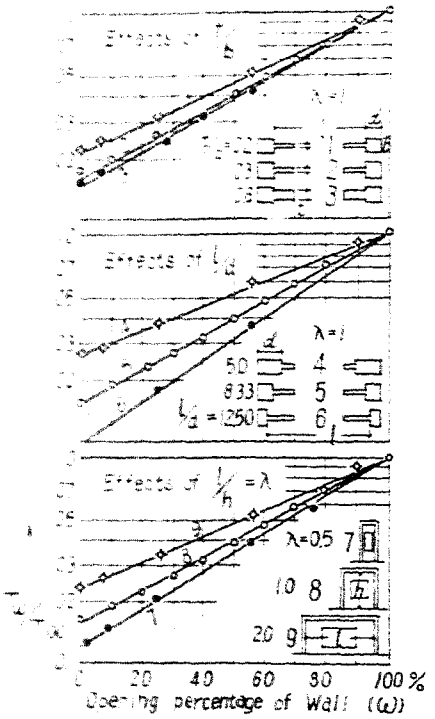

Fig. 6

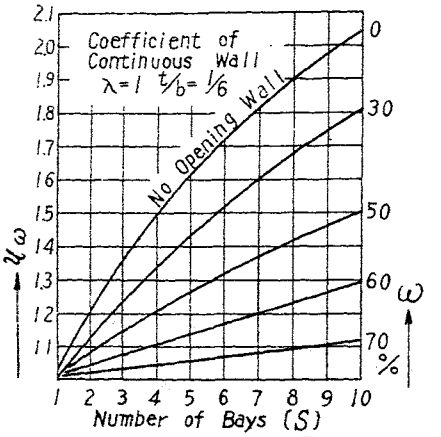

Fig. 7

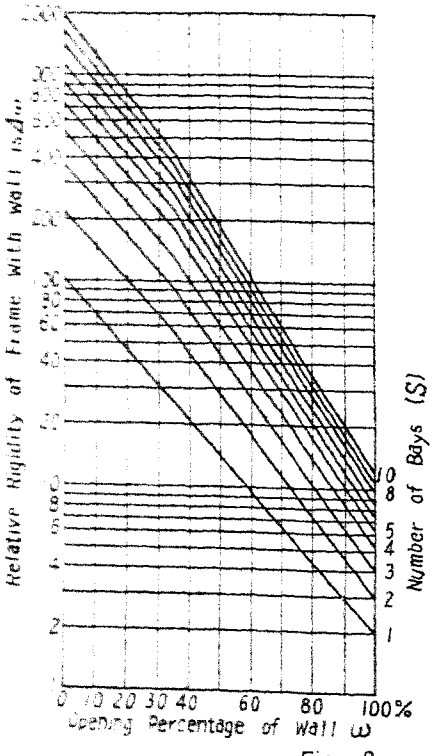

Fig. 8

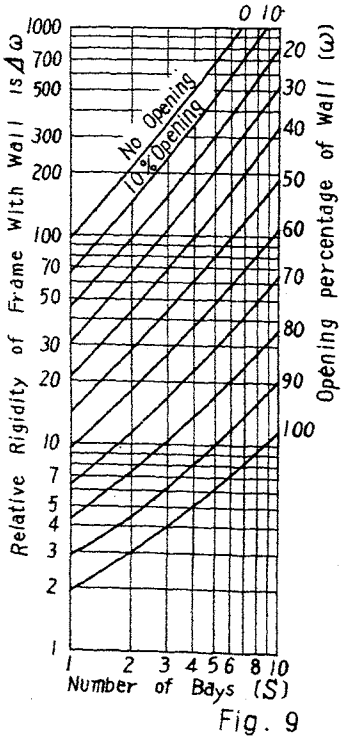

Fig. 9

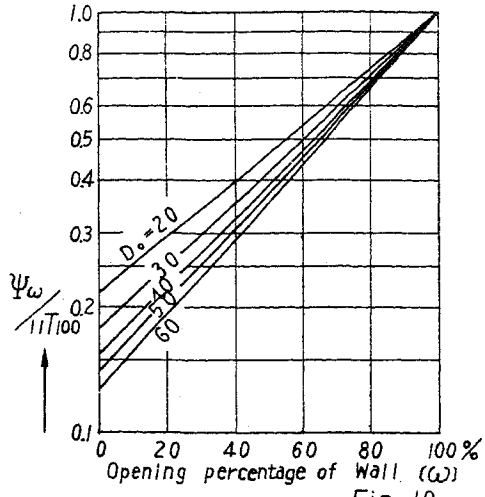

Fig. 10

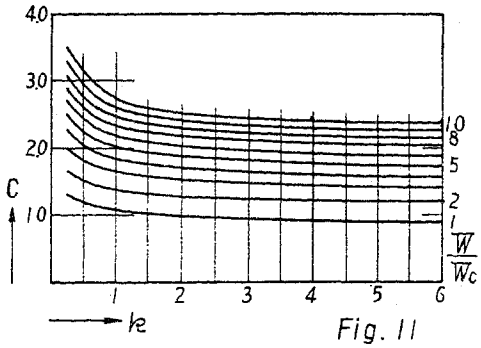

Fig. 11

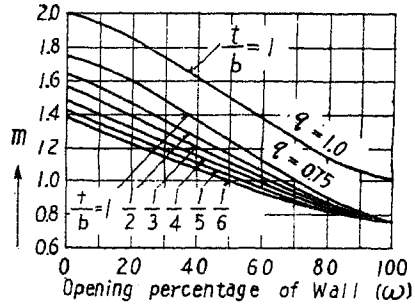

Fig. 13

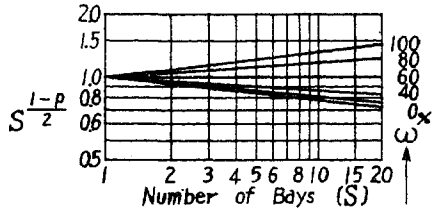

Fig. 12

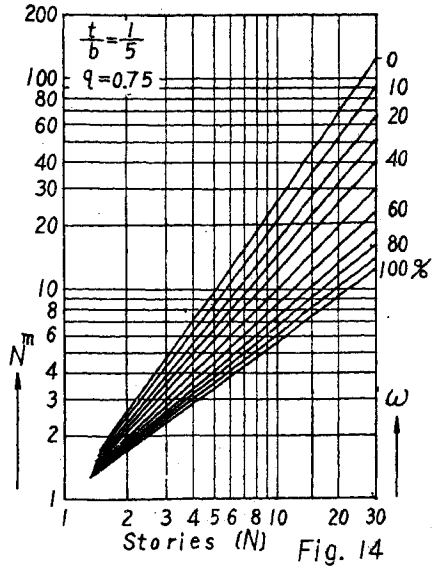

Fig. 14

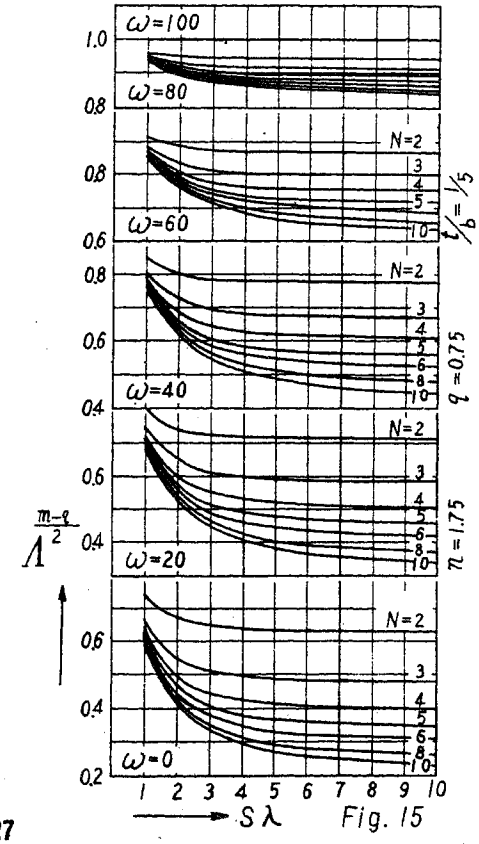

Fig. 15

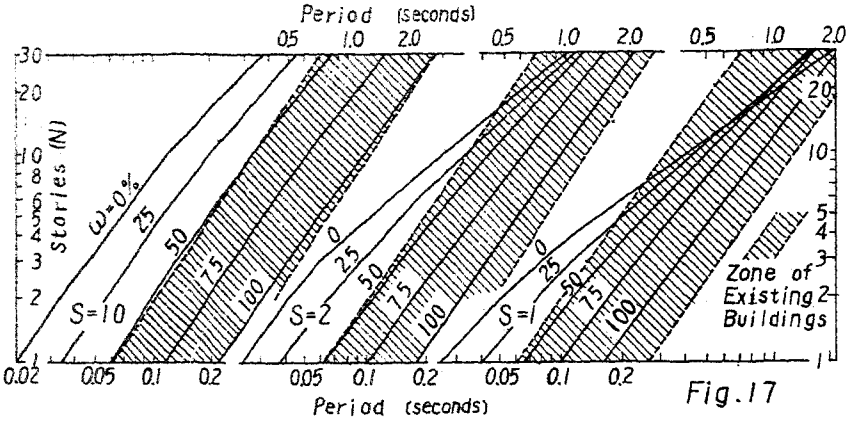

Fig. 17

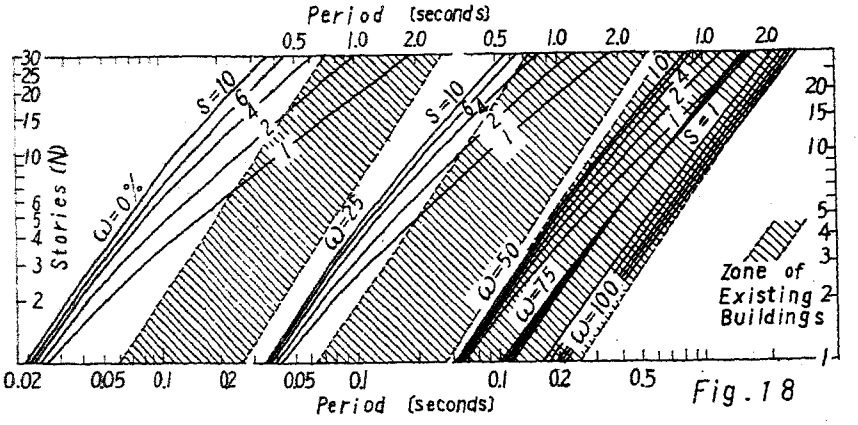

Fig. 18

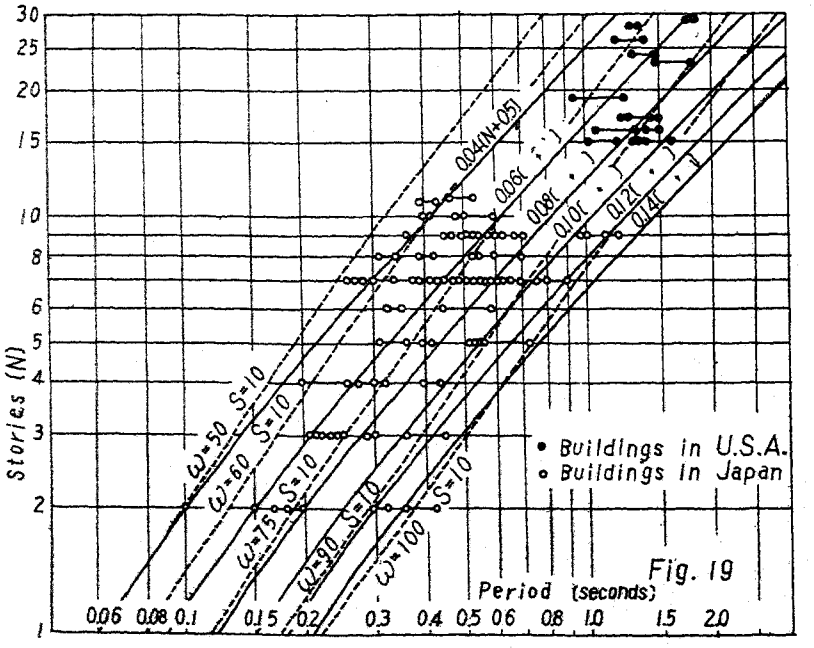

Fig. 19