A STUDY IN SEISMIC RESISTANCE OF FRAME STRUCTURES

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SUMMARY

The paper deals with an experimental and theoretical study of seismically resistant frame structures (frame,frame-braced, braced). Experiments have been conducted on simulated and live structures. Dynamic loading of structures has been done using a vibration machine. The subject of study here is the effect of vertical and horizontal rigidity membranes and vertical snapping upon the dynamic characteristics and rigidity of structures. New techniques have been developed to determine dynamic depêndence between the forces of storey rehabilitation and deformation and to find out experimentally the dynamic rigidity of the base.

INTRODUCTION

Multi-storey RC frame structures are currently very widely represented in seismically resistant construction of residential and public buildings. Years of experience in their design and construction clearly show the frame-braced and braced systems to be the most economical and reliable among the frame-type structures. In these structures membranes or rigidity nuclei are specifically arranged to sustain seismic loading. Unlike the design of frame systems using sophisticated techniques of structural mechanics,no technically acceptable procedures have been developed for anti-seismic design of frame-braced and braced structures. Experiments have yielded multiple indications of discrepancies between the estimated and the real rigidity values in frame-braced and braced systems,the most complicated factors being the accounting for the effect of rigidity of linkages,the "foundation-base" system as well as establishing the "force-displacement" dependence in dynamic loading.

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EXPERIMENTALLY DETERMINED EFFECT OF VERTICAL AND HORIZONTAL MEMBRANES UPON THE RIGIDITY PARAMETERS OF FRAME SYSTEMS

Experiments have been conducted on spatial organic glass and RC 9-story models in the scale of I:50 and I:5 resp. and on a 2-story spatial fragment of frame structure in real size (Figs. I,3). Dynamic testing has shown both the floors and membranes to produce a far greater effect on horizontal rigidity in braced rather than in frame-braced structures. In structures having supporting crossbars and transformed into frame-braced systems through introduction of membranes,a stage-by-stage inclusion of floors and then rigidity membranes yielded reduction of basic tone period I.I5 and I.20 times respectively while for structures with braced crossbars transformed into braced systems after membrane introduction the reduction was I.36 and 2.33 times,the decrement of oscillations being increased I.7 times on average. It is easy to see that the vertical membranes,in braced systems in particular have a greater effect on rigidity parameters of structures than the horizontal membranes or floor discs. For a more detailed study of the effect of vertical membranes on the rigidity parameters of frame systems in horizontal loading,testing has been done on a 9-storey RC model with storey-by-storey installment of membrane panels in one frame span along the middle axis. In this process oscillation shapes have been determined for frame-braced and braced systems together with the variation of dynamic rigidity of storeys (Fig. 2). The results show significant variations in the model's oscillation shapes for intermediate storeys. However on completing the assembly of membrane panels on all nine floors these differences are smoothed for the lower tone but are becoming more substantial with the rising number of tone. The effect of rigidity membranes on the oscillation forms is greater in the braced system than in the frame-braced one,the same being observed with regard to the dynamic rigidity of storeys. In the braced system the membrane resulted in an increased average dynamic rigidity of storeys by 9.35 times,while the frame-braced one showed an increase of I.78 times. In both cases the dynamic rigidity of stories along the vertical dimension of the model has proved to be variable:the rigidity is decreased towards the top of the model with a quasi-linear regularity. The ratio of dynamic rigidity of the first storey to the rigidity of the ninth storey for the frame-braced system was 3.3 with the braced one 2.6. Dynamic rigidity of the storey is understood as inertial transversal force arriving to the given storey and causing it to skew. With regard to this definition the vertical rigidity drop may probably be explained by added vertically directed dynamic skewing due to some rotation of floors caused by general bending during vibration. Besides,the storey rigidity variation is also caused by the differing levels of their snapping by vertical forces,the lower storeys being squeezed more than the higher. Experiments have established the vertical loading to result in an increase of the horizontal rigidity of the lower storeys I.6 times with the upper stories I.3 times (Fig. 2).

EXPERIMENTAL TECHNIQUES OF DETERMINING THE DYNAMIC RIGIDITY OF BASE

In calculating seismic resistance of buildings and structures consideration is to be made of the structure-to-ground interaction. Solution of this problem is linked with the determination of dynamic rigidity of the base during the horizontal vibrations of the structure. Ordinarily horizontal rigidity of base is determined theoretically using the solution of the dynamic contact problem in the elastic theory. In this process

the real picture of the foundation-to-ground interaction undergoes a significant simplification neglecting the depth factor and the complicated geometry of the foundation,non-uniformity and plastic deformation of the ground. All these factors can be accounted for within the experimental determination of base rigidity.

It is suggested that the dynamic rigidity of base C be determined through vibrational testing of real structures and their fragments,the vibration machine being installed on the top floor (Fig. 3). Base rigidity is determined from the relation:

$$C=\frac{F}{u}=\frac{\sum_{i=I}^{n} m_i \ddot{y}_i}{u} = w_0^2\frac{\sum_{i=I}^{n} m_i y_i}{u} \qquad (I)$$

where F is transversal inertial force generated at foundation level by vibrational load; $y_i,\ddot{y}_i$ is displacement and acceleration of the i-th storey; u is foundation displacement; m_i is the mass concentrated on the i-th storey.

It follows from (I) that experimental determination of rigidity of base C necessitates measurement of acceleration of all storeys and the foundation displacement. On the 2-storey fragment of the frame structure (Fig.3) in resonance mode with differing weights of disbalance on vibrator shafts measurements were made of the foundation displacements and storey acceleration together with calculations of dynamic rigidity of foundation by the formula (I). The results are presented in the Table.

Table

circular frequency of foundation vibration (s^{-1})	foundation displacement (mm)	transversal force(kN)	Calculated rigidity of foundation C (kN/mm)
69.78	0.015	200.0	13330
69.78	0.018	238.5	13250
68.26	0.027	290.6	10760
68.26	0.034	348.8	10260

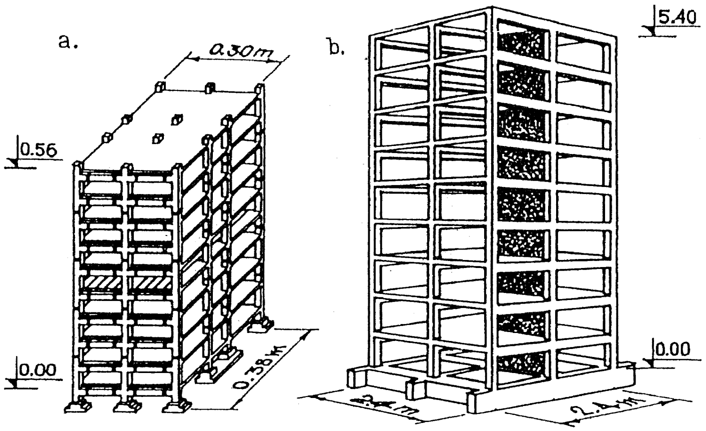

Fig.I.Models of 9-storey frame structures
a - organic glass, I:50
b - RC, I:5

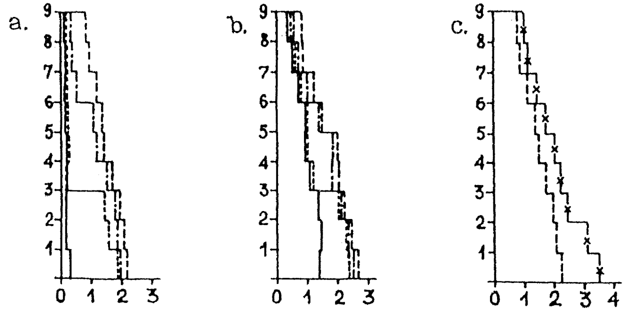

Fig.2.Initial dynamic rigidity of storeys, $a_K \cdot 10^{-7}$, N/m
a,c- braced system
b - frame-braced system

——— rigidity membrane missing
.... membrane panels on I,2,3 storeys
-·-·- membrane panels on I,2,3,4,5,6 storeys
- - - - membrane panels on all storeys
-x-x- ditto, with vertical loading

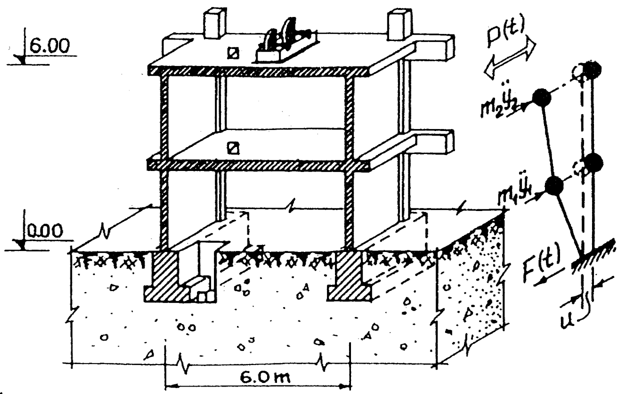

Fig.3.Life-size 2-storey fragment for determining dynamic rigidity of base

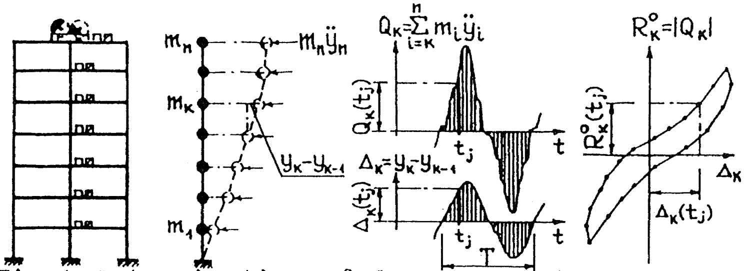

Fig.4.Determination of dependence "rehabilitating force - deformation" for dynamic loading

□ - seismometers showing displacement
⊠ - seismometers showing acceleration

As is seen from the Table the dynamic rigidity of base has a substantial dependence on the level of its loading. Under the load increased I.3 times the initial value of dynamic rigidity is decreased I.3 times. Let us compare the experimentally obtained value C with the theoretical. The initial value of rigidity C obtained using an analytical solution of a flat contact problem at small frequencies is as follows (Ref. I):

$$C=2\pi C_2^2 p(I-d^2)h-\frac{\pi b^2}{4}p(I+d^4)\ w_0 h; \qquad d=C_2/C_I \tag{2}$$

where: C_I, C_2 is rates of propagation of longitudinal and transversal waves in the ground; p is ground density; w_o is circular frequency of foundation vibration; 2b, h is width and length of foundation.

The tested fragment had two strip-type foundations with the foot measuring I.4 x 7.4 m which in calculation are being substituted by an equivalent foundation measuring 2.8 x 7.4 m. The base ground is macrofragmentary with basalt inclusions: C_2 = 800 m/s, p = I.6 kN $\cdot$s$\cdot$m $^{-4}$. The value C = II950 kN/mm is calculated using formula (2) and deviates by I5 per cent from the experimental value obtained at the initial low level of loading. The experimentally obtained values of base rigidity, it is suggested, should be applied when solving the problem of ground-to-environment interaction (Ref. 2).

EXPERIMENTAL TECHNIQUES YIELDING THE DEPENDENCE "REHABILITATING FORCE - DEFORMATION" FOR FRAME SYSTEMS

It is common knowledge that the regularities of dynamic loading which in particular is seismic action have a qualitative difference from the static one. In this connection more accurate design patterns and descriptions of the structures' actual behaviour can be produced using the characteristics of rehabilitating forces for each storey of the building rather than for individual structural elements with consideration of all supporting and unloaded elements, yield in their conjugating joints, variable vertical snapping, forces of internal resistance and other factors inherent to dynamic loading (Ref. 3).

Presenting the design pattern of the structure in the form of a vertical squared beam with discrete masses concentrated at the levels of interstorey floors being displaced under vibration in parallel with one another in horizontal planes, we shall have the rehabilitating forces for any storey stipulated by the desplacement difference between the given and the adjoiningstoreys, i.e. by deformation (dynamic skew) of the storey (Fig. 4). To obtain the dependence of rehabilitating force on the deformation of a particular storey in the process of dynamic loading it is suggested to record the picture of change in time of the deformed state of all storeys in the structure. This can be done using a vibration machine mounted on the top storey floor.

For the accepted design pattern the differential equations of displacement will have the following form (Ref. 4):

$$Q_k(t)+R[y_k(t) - y_{k-I}(t)] + C_k[\dot{y}_k(t)-\dot{y}_{k-I}(t)] = P(t) \quad (3)$$

where: Q_k is transversal inertial force of the level of the k-th floor; R_k; C_k are rehabilitating force and internal resistance force of the k-th floor respectively; P(t) is the disturbing force of the vibrator; $m_k, y_k, \dot{y}_k, \ddot{y}_k$ are mass, displacement, speed and acceleration of the k-th storey resp.

Determination of dynamic dependence of rehabilitating force on storey deformation is based on the equivalence of the transversal inertial force at the level of a given storey and internal forces on the same level, vis.: the rehabilitating force and the force of resistance. The disturbing force of vibrator can be disregarded being negligible compared with transversal structure-generated inertial forces. However, if needed, the force P(t) can be taken from the equation (3) which can then be rewritten as follows:

$$R_k^o(t) = -Q_k(t) \quad (4)$$

where $R_k^o(t)$ is the sum of internal forces which can be termed as a generalized dynamic rehabilitating force.

Thus, to determine the values $R_k^o(t)$ at the level of a given storey for any moment, one has to find the transversal inertial force for this moment at this level. Determination of the dynamic dependence between the rehabilitating force and deformation (skew) of the story for any moment can be done if deformation of the given story is found for this very moment. So, a study of dynamic loading necessitates simultaneous recordings to be made of accelerations and displacements of all floor levels of the structure under investigation. The related oscillograms show a section for a randomly chosen complete cycle of this vibration shape. The moment of time matching the selected cycle has to be the same for all storeys. On selected fragments (equal to a period of one complete oscillation) displacements and accelerations are tabulated with a constant step. Tabulation results in determining the displacement $y_k(t_j)$ and acceleration $\ddot{y}_k(t_j)$ for a given storey at every step. Subsequently a calculation is made of inertial forces at the same moments by the formula:

$$S_k(t_j) = m_k \ddot{y}_k(t_j) \quad (5)$$

where m_k is the actual mass of the k-th storey. Tabulated values of displacements and inertial forces facilitate calculations of tabulated dynamic skews and transversal inertial forces respectively for each storey by the formulas:

$$\Delta_k(t_j) = y_k(t_j) - y_{k-I}(t_j) \quad (6)$$

$$Q_k(t_j) = \sum_{i=k}^{n} S_i(t_j) = \sum_{i=k}^{n} m_i \ddot{y}_i(t_j) \quad (7)$$

In these formulas displacements and inertial forces are taken with their signs. Further a chart is plotted of the dependence of transversal inertial forces or, which is the same, of the generalized dynamic rehabilitating forces on the skews for each storey of the building in the form of closed curves (Fig. 4), reflecting the operation of storeys at a given stage of dynamic

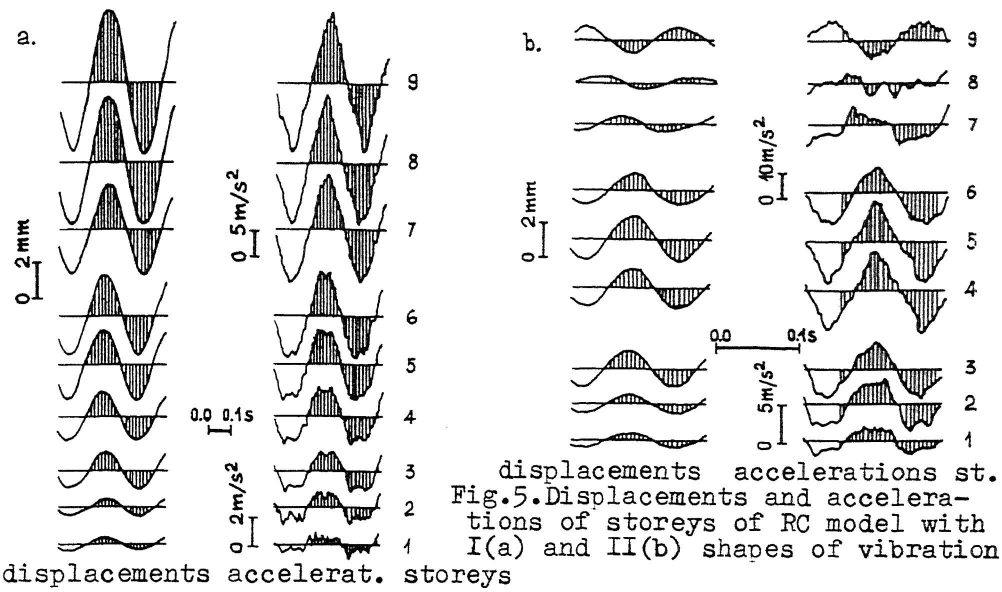

Fig.5. Displacements and accelerations of storeys of RC model with I(a) and II(b) shapes of vibration

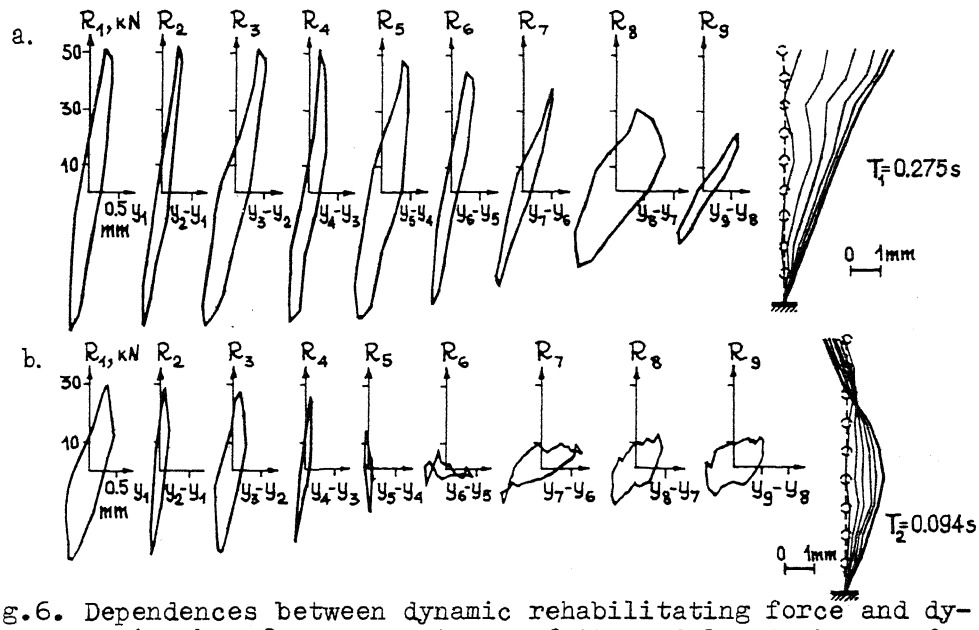

Fig.6. Dependences between dynamic rehabilitating force and dynamic skew for every storey of the model and shapes of its elastic axis at one stage of testing with I(a) and II(b) shapes of vibration.

loading. Mathematically that means an exclusion from two functions $Q_k(t)$ and $\Delta_k(t)$ of the argument t and the determination of the new dependence $Q_k(\Delta_k)$. The accuracy of the resulting curves will depend on the selected step of tabulation which should not exceed T/I0, where T is the period.

The presented procedure for determining the characteristic of rehabilitating force includes an integrated account of effects produced by internal resistance, structural friction in rigidity joints of supporting and unloaded structures, vertical snap variables, loading rate and spatial operation. The procedure can be used not only in the resonance mode of loading but also with other frequencies of constrained oscillations enabling a more detailed study of the effect of loading rate on the characteristic of the dynamic rehabilitating force. The procedure is usable for forming a picture of vertically directed dynamic deformation for different types of structures during earthquakes by supplementing the right-hand part of the equation (4) with inertial loadings associated with general horizontal displacement of the structure

$$R_k^o(t) = -Q_k(t) - \sum_{i=k}^{n} m_i \ddot{y}_o(t) \quad (8)$$

where $\ddot{y}_o(t)$ is ground acceleration on the earthquake accelerogram. The above procedure using a 9-storey RC model has yielded dynamic dependences between rehabilitating force and deformation for one of the testing stages. Fig. 5 shows sections of resulting oscillograms with I and II shapes of vibration. These have provided a basis for plotting the dynamic dependences of rehabilitating forces from the skews for each storey of the 9-storey model individually by the I and II type of oscillation (Fig. 6). They reflect the nature of dynamic deformation of the model at a given stage of loading along the frame-braced pattern. These Figs. also show the shapes of the elastic axis of the model corresponding for a quarter of a period to six points of tabulation. This leads to the assumption that with a vibrating model characteristic shapes of a certain tone are manifested when the storey displacements approach their max. values for a given tone. However in the intermediate stages there are violations of the vibration shape characteristic for the given tone with the adjoining storeys oscillating with a phase shift to one another affecting formation of dynamic skew and causing their non-uniformity along the vertical of model. This is the cause of differing openings of loops describing dynamic deformation of the model's storeys.

REFERENCES

I. Khachian E.E., Ambartsumian V.A. Dynamic Models of Structures in the Theory of Seismic Resistance (in Rus.) M.: Nauka, I98I, 204 pp.

2. Khachian E.E., Ambartsumian V.A., Goroyan A.T. A Study of Seismic Effect on Structures with regard to loading rate and structure ground interaction. Proc. of the 7 Europ. Conf. on Earthquake Engineering. Athens, Greece, I982, vol. 2, pp. 577-582.

3. Khachian E.E., Melkumian M.G. Methods of Determining the Dynamic Dependence "rehabilitating force-displacement" (in Rus.). Doklady Acad. Nauk Arm. SSR, I982, Vol. LXXIV, No. 2, pp. 72-77.

4. Khachian E.E. Seismic Action Affecting Tower Blocks and Structures. Yerevan: Aiastan, I973, 327 pp.