Research on Behaviour of Reinforced Concrete Constructions under the Effect of Seismic Load

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Abstract. The paper presents the results of an investigation conducted in the Laboratory of the Chair of Seismic Stability of Reinforced Concrete Constructions and Bridges of the V.I. Lenin Georgian Polytechnical Institute, in 1960-1967. The object of the investigation was to study the behaviour of reinforced concrete constructions under the action of seismic loads, to determine their actual supporting capacity under conditions of dynamic actions, and to work out recommendations on the refinement of computation procedure. The investigation studied consists of the experimental and theoretical parts.

Introduction. The method of practical computation of reinforced concrete structures for seismic loads, in currrent use, is based on the theory of linear vibrations. Estimation the seismic stability of constructions is carried out by means of comparing the maximum (peak) efforts, determined by spectral curves, with the static supporting capacity of cross-sections. This method is largely arbitrary: in particular it leaves out of consideration the reserves of strength produced by the circumstance that the extremely brief duration of maximum effort action may prove insufficient for the development of limiting plastic (residual) deformations [1,2]. The presence of such reserves of strength in reinforced concrete constructions under the action of seismic loads is confirmed by a number of investigations and experience of earthquakes.

For the computation of seismic stability to be better grounded it is necessary to take into account the non-linear character of vibrations of reinforced concrete constructions under intensive dynamic loads and to specify the general picture of their behaviour up to the stage of failure. At present much attention is given to experimental investigations in this field [3,4,6,7]. The present authors have conducted such investigations with coarse-size specimens of ordinary reinforced concrete.

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Objects of investigation. Single-stage and two-stage reinforced concrete single-span frames of I.50 m in span and 2.20 m in height were subjected to test. The diagrams of frames tested are given in Fig.I,a. The stiffness of cross-bars and of the pedestal considerably exceeds that of posts. Owing to this the deformation and supporting capacity of frames under the action of horizontal loads are determined by the stiffness and strength of posts. Thereby the plastic redistribution of efforts in the frame elements as well as the reserves of strength connected with the redistribution are eliminated. The frame posts of rectangular section have symmetrical reinforcement of round smooth soft steel bars. Representative diagrams of deformations of reinforcement steel are shown in Fig.2. The limit of the yield poind of steel, according to the data of the specimens tested is equal to 2625 to 3I25 kg/sq cm. The strength of the concrete of frames at the time of the test was I52 to 366 kg/sq cm. Six single-stage and six two-stage frames were tested in all. Besides, 2.20 m long cantilever bars (four specimens of I5x8 cm in section and seven ones of I5xI5 cm in section) were additionally tested (Fig.I,b).

Static tests of frame specimens were carried out for the action of concentrated forces applied at the level of one of the cross-bars. The forces were created by means of weights suspended from a pulley (Fig.3,a). The test process consisted of the sequential cycles of action, the act of loading being carried out in one or an opposite directions. In each cycle the loading was increased step by step, from zero to P_{max} . After two or three cycles of loading the tests were repeated with on increased P_{max} ; at the final stage this value reached 0.6 to 0.8 of the theoretical failure load. During the tests horizontal displacements of frame cross-bars and relative deformations of concrete and post reinforcements close to the levels of fixing in the cross-bars and the pedestal were measured, as well as the opening cracks. Static test of cantilever specimens was carried out in an analogous manner.

The diagrams of deformations of test specimens were plotted on the basis of experimental data. Typical diagrams are given in Fig.4. The results obtained show that the diagrams of deformation of tested reinforced concrete specimens , with a static load, in all cases have the form of hysteresis loops. However, the character of diagrams may be different: it essentially depends on the initial crack state and crack development during the process of loading. A non-linear diagram of the "rigid" type shown in Fig.4,b is typical of the instance of alternating deformations; the breaking of the loading line of the diagram is apparently accounted for by the increase of the stiffness of the element as a result of the closing of cracks on the side of the compressed edge. Diagrams of the same form were also obtained in study [6].

Energy losses during deformations were estimated by the size of the hysteresis loop area. Computations showed that the energy absorbed during one cycle reaches considerable values - up to 70 per cent of the maximum elastic energy of the cycle. The experiments also showed that with an increase of load the stiffness of experimental elements decreases at the expence of gradual development of cracks. These circumstances attest to the essentially non-linear work of the tested specimens under static load. The tests of reference specimens which were brought to failure showed that the actual supporting capacity of frames with a static load is near to the calculated capacity.

<u>Dynamic test</u> of specimens were carried out on the seismic platform of the Georgian Polytechnical Institute [5]. During the dynamic tests additional weights of 500 kg each were suspended to the cross-bars of frame specimens. This permitted consideration of the frames as systems with one or two degrees of freedom. Inertial action on the frame, thereby, reduced to concentrated horizontal forces at cross-bar levels. The frames were placed on the seismic platform and tested for vibrations on their plane. The scheme of the dynamic tests of frame specimens is given in Fig.3,b. The cantilever specimens were tested without additional weights.

Dynamic test were carried out at the regime of free and forced vibrations. To excite free vibrations the frame cross-bars were drawn off by weights and then suddenly released; the tests were held at different displacement values of frames. Such tests were made several times: before the beginning of the tests for forced vibrations and then, during the intervals between them.

The tests for forced vibrations were carried out under two conditions of platform motion:

(a) vibrating oscillations with constant amplitude and alternating frequency; the latter was changed smoothly from a minimum (about I cps)to a maximum value (6 to 10 cps) and again decreased to a minimum, with the frequency passing the resonance zone of the specimen. The tests were made in several cycles, with a gradual increase of the oscillation amplitude of the platform up to the failure of the specimen.

(b) impact oscillations caused by a blow of the ram of a pendilum pile-driver against the frame of the platform (base of the specimen). These tests were also carried out in several cycles, with gradual increase of the ram mass and blow height.

During the dynamic tests the displacements of frame cross-bars were measured by electric deflectometers of cantilever type and the relative reinforcement deformations - by resistance transducers. Readings of these instruments were recorded on an oscillograph film.

Representative vibrating oscillograms of frame specimens obtained during the tests are given in Fig. 5.

The oscillograms of free vibrations showed that the frame specimens with additional weights fixed on the cross-bars may be represented with reasonable accuracy in the form of dynamical systems with one or two degrees of freedom. The vibrations of single-stage frames had a clearly pronounced single-tone character. In a number of cases the influence of the second tone is registered on the oscillograms of free vibrations of two-stage frames. At the beginning of the tests the actual periods of the natural vibrations (of fundamental sound) of frame specimens had values from 0.14 to 0.66 sec., depending on the size of additional weights on the cross-bars. With larger amplitudes the natural periodes of some frames provided to be 2-15 per cent higher than those of smaller amplitudes. For purposes of comparison theoretical values of natural periods were determined; they were calculated by formulae for linear systems with one or two degrees of freedom, the coefficients of stiffness being taking according to the data of static tests (from the averaged deformation diagram with corresponding amplitude). The difference between the theorectical and experimental values of natural periods of fundamental sound in most cases did not go beyond the 10-15 per cent limit, a greater difference occuring only in single cases. The theoretical and experimental values of the second tone of two-stage frames are also in good correlation. This shows that the initial values of natural periods of reinforced concrete constructions may, with reasonable accuracy for practical purposes, be calculated by the theory of linear vibrations and that the static and dynamic stiffnesses of frame specimens are close one to the other. The latter circunstance is also borne out by the results of cantilever specimen tests. It should be noted, however, that in order to obtain reliable theoretical values of periods correct determination of stiffness of the reinforced concrete element, with account of the presence and character of cracks, is of great importance.

The decrement values of free vibrations of tested frame specimens (in the initial period) vary within the limits of 0.12 to 0.46. These values correspond with ordinary values of decrement for reinforced concrete constructions. They correlate satisfatorily with the values of energy absorption coefficient, determined by the hysteresis loop of deformation static diagrams.

Free vibration oscillograms, recorded in the intervals between cycles of vibration (or impact) tests, enabled to follow the change of natural periods and decrements of specimens in the process of dynamic action. In all cases an increase was noted of natural periods after forced vibrations, which is accounted for by a gradual decrease of stiffness at the expense of development of cracks. As observed above, decrease of specimen stiffness was directly ascertained by repeated cycles of increased load in the process of static tests. Increase of periods as a result of dynamic achion proved to be quite substantial: the near-to-failure stage the values of natural periods of frame specimens exceeded the initial values by 12 to 46 per cent. The chage of vibration decrements is of a more complicated character. Both an increase and decrease of decrement were observed in the tests in the process of dynamic achion. During tests of some frame specimens the vibration decrement at first increased and then decreased. So far it proved impossible to establish any regularities in this field.

Resonance curves for frame specimens were plotted according to the results of vibration tests. Some of these curves are given in Fig.6. In some cases, the so-called vibration "bbreak-down" (amplitude leap) characteristic of forced vibrations of non-linear systems was observed on the oscillograms. Fig.5,d shows a section of one of such oscillograms where a sharp decrease of vibration amplitude of frame cross-bars, with some negligible decrease of the outer-action period (motion of platform) is well-defined. The non-linear character of forced vibrations is also confirmed by the shape of resonance curves.

The supporting capacity and the failure character of frame specimens were studied by means of vibration and impact tests. The tests showed that during dynamic action the resistance of frames was higher than during static loads. In the process of tests frame vibrations were brought to such an intensity that the maximum inertial load in each cycle of vibrations substantially exceeded the limit (static destructive) load. At the same time the amplitudes of reinforcement deformations were far beyound the scope of elastic deformations, while the amplitudes of cross-bar displacements reached 1/28-1/30 of the height of posts; the cross-bars of frames received a residual displacement of the order of 15-20 mm. In spite of this the frames did not lose their supporting capacity and were capable of resisting horizontal forces. For a dynamic destruction of the specimen the intensity of vibration or impact action had to be increased and repeated several times, failure being cause by a progressive increase of cracks and the crushing of concrete in the fixed sections of posts or in the frame joints. The process of destruction was gradual in character. The definite point of time or the dedefinite intensity of action, during which the loss of supporting capacity of specimens is clearly revealed, has not been established.

The increase of dynamic supporting capacity in comparison with the static capacity may partially be explained by the increase of the yield point of reinforcement during rapid loading. But for the velocities of loading that took place in the tests the influence of this factor is immaterial. The circumstance referred to at the beginning of this paper plays the main role: by reason of the rapid change of loading the limit residual deformations of reinforcement have no time to develop, or different sign residual deformations are mutually liquidated.

The tests conducted do not, of course, cover all the aspects of the problem; in particular, the influence of axial forces in the posts may be essential, as well as the nature of reinforcement, the kind of action, etc. But, data of the tests to some extent do characterize the dynamic behaviour of reinforced concrete.

Theoretical researches were based on the results of the tests carried out. On the basis of these tests it can be assumed that the loss of the supporting capacity of reinforced concrete constructions under the action of bending moments, generated by the seismic (dynamic) load, may be caused by three reasons 1) :

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1) Destruction from transverse forces (on slanting sections), or from disturbance of cohesion between reinforcement and concrete is to be considered separately.

(a) Destruction of concrete from compression or alternating loads.

(b) Destruction of reinforcement under alternating loadings beyound yield point (cyclic destruction [8]). In the tests this kind of destruction was not observed, but it can take place in real constructions.

(c) Development in constructions of inadmissible residual displacements at the expense of accumulation of plastic deformations in the reinforcement.

The first two causes may be eliminated by a corresponding provision of safe stresses on the basis of experimental data. To determine residual displacements it is necessary to have a computation of the construction as a dynamic system. As is seen from the experiments conducted the most suitable computed model for reinforced concrete constructions is the non-linear hysteresis system with alternating parameters, in which change of paramenters is conditioned by the nature and intensity of action. For practical calculations such systems are most conveniently described with the help of polylinear diagram, the parameters of which change in each cycle. The possible forms of diagrams for some i th cycle of vibrations are given in Fig.7. The parameters of diagrams (P_{1i} , P_{2i} , α_{1i} , α_{2i} , α_{3i} , etc.) and the order (law) of their change from cycle to cycle are to be established in accordance with the experimental data. In the first approximiation these parameters can be selected so as to ensure increase of the natural period during vibrations observable in experiments.

The method of computation described above is sufficiently universal, permitting coverage of various kinds of diagram deformations. It is evident that its application in practice will be possible only after of a large body of experimental data have been accumulated and their detailed analysis. Preliminary calculations made with the aid of electronic computers have shown that in this way satisfactory computational description of the behaviour of reinforced concrete constructions under some modes of dynamic actions may be obtained.

References

I. Kartsivadze G.N. On the Method of Computation of Reinforced Concrete Constructions for Intensive Dynamic Action. Proceedings of the V.I. Lenin Georgian Polytechnical Institute, No.5, (110), Tbilisi, 1966. (in Russian)

2. Avalishvili L.N. Experimental Investigation of the Work of Reinforced Concrete Frame Constructions in Conditions of Seismic Effect. Collected Papers:"Perfection of Methods of Calculation and Designing of Buildings and Structures Errected in Seismic Area. Tbilisi, 1967. (in Russian)

3. Korchinski I.L. Rzhevski V.A. Study of the Strength of Reinforced Concrete Bending Elements under the Action of Seismic-type Loads. J. "Beton i zhelezobeton", 1966, No.I. (in Russian)

4. Zhunusov T.Zh., Shcherbina V.I. Studies of the Strength of Reinforced Concrete Bending Elements under the Action of Dynamical loads. Collected Papers: Materials of a meeting on earthquake-proof construction, Alma-Ata, 1967. (in Russian)

5. Kartsivadze G.N. Seismic Platform of the V.I. Lenin Georgian Polytechnical Institute. Proceedings of the Higher Educational Establishments of the Ministry of Higher and Specialized Secondary Education. "Stroitelstvo i arkhitektura", 1961, No.3. (in Russian)

6. T. Shiga, I. Ogawa. An Experimental Study of Dynamical Behaviour of Reinforced Concrete Frames, Proc. of Japan Earthquake Engineering Symposium, Tokyo, 1966

7. H. Acyama, T.Endo, T. Mihami, Behaviour of Reinforced Concrete Frames Subjected to Reversal of Horizontal Forces. Proc. of Japan Earthquake Engineering Symposium, 1966, Tokyo, 1966.

8. Hodge P.G. Plastic Analysis of Structures, N.Y., Toronto, London, 1959.

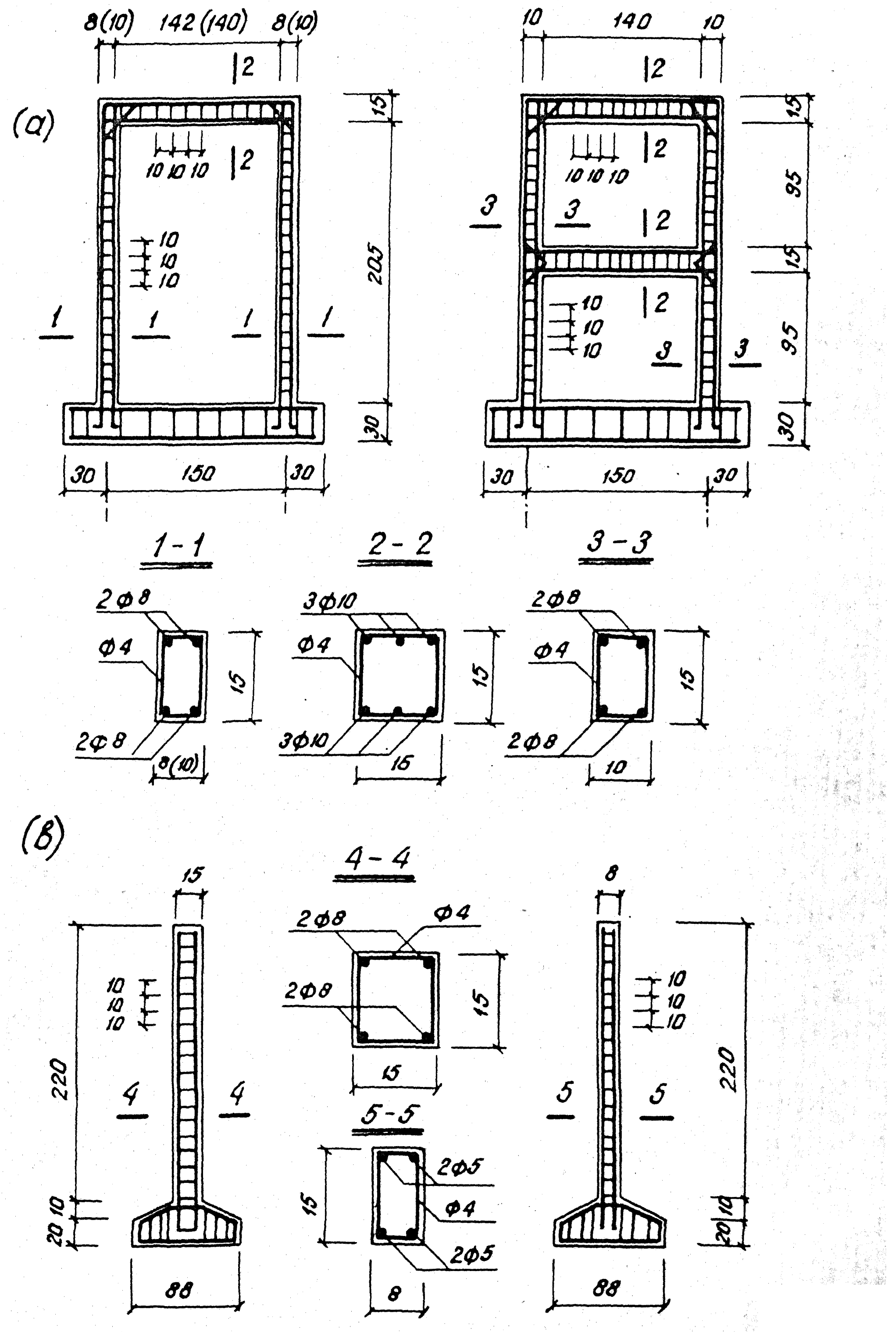

Fig.1
Schemes of tested specimens:
a) frame specimens; б) cantilever specimens.

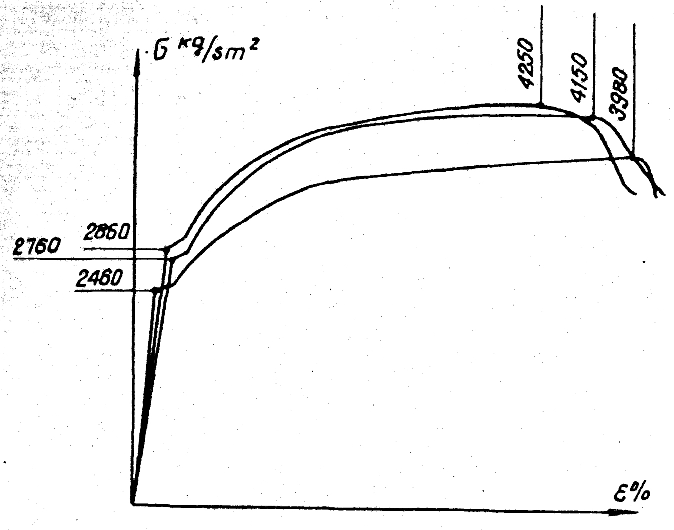

Fig.2

Diagrams of reinforcement steel deformations.

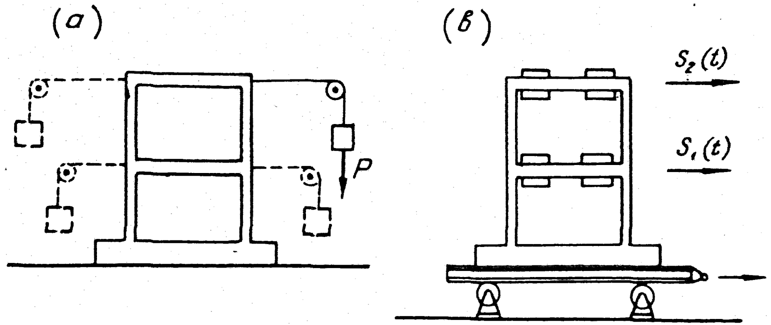

Fig.3

Schemes of frame specimen tests:
a) static tests; б) dynamic tests.

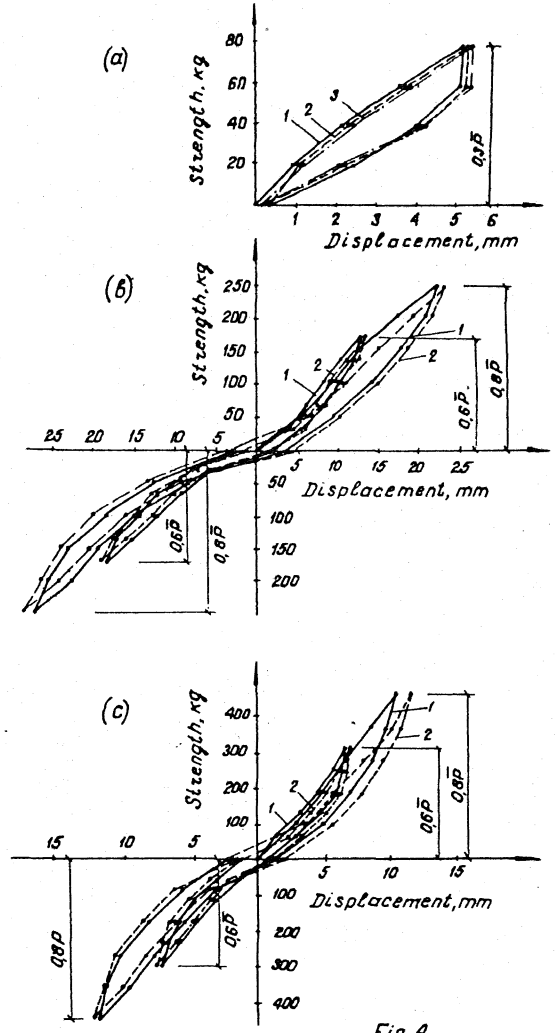

Fig. 4

Diagrams of frame specimen deformations under the static load:
a) single-stage frame-displacement of cross-bar;
б) single-stage frame-displacement of cross-bar;
c) two-stage frame - displacement of the upper cross-bar.

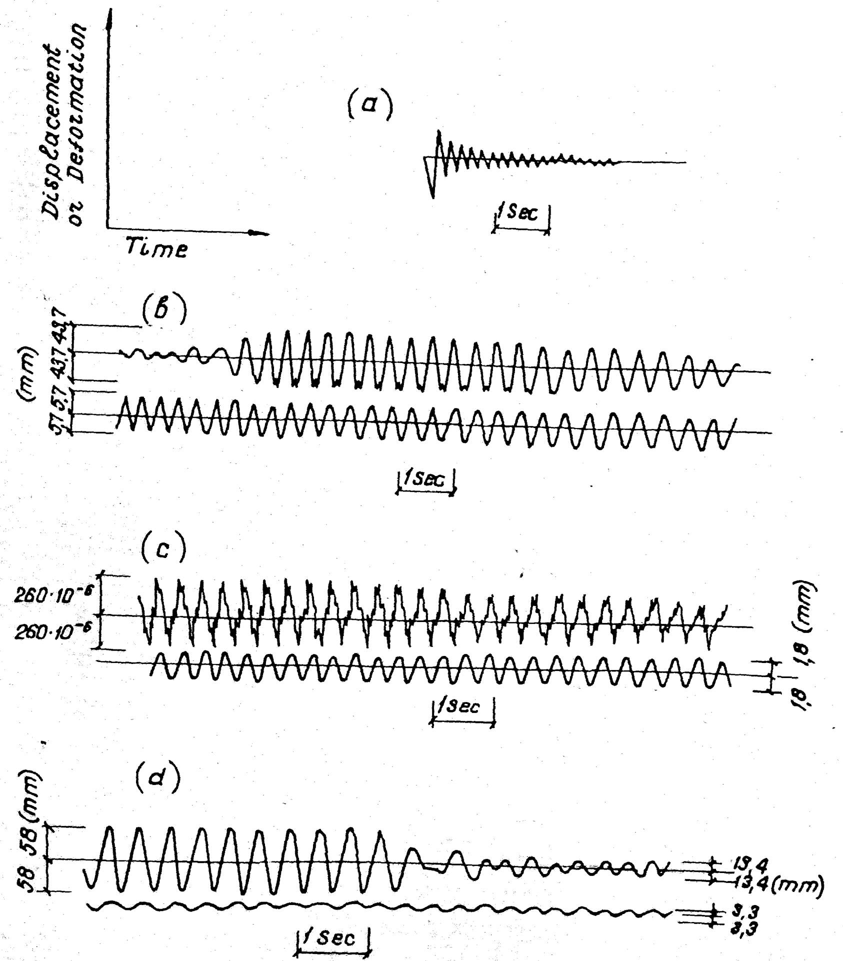

Fig.5

Representative oscillograms of frame specimen oscillations:

a) free oscillations of single-stage frame-displacement of cross-bar;
b) vibrating oscillations of single-stage frame-displacement of cross-bar;
c) vibrating oscillations of two-stage frame-deformations of post reinforcement in the upper joint;
d) vibrating oscillations of two-stage frame-displacement of upper cross-bar;
Lower lines of oscillograms (b), (c), (d) - displacement of platform.

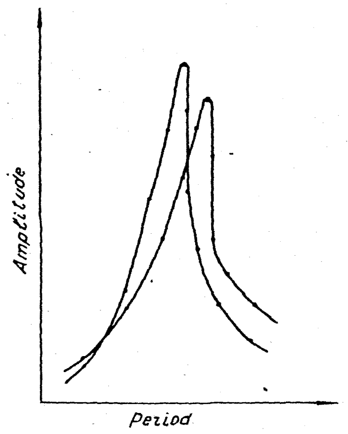

Fig.6

Resonance curves of frame specimens tested.

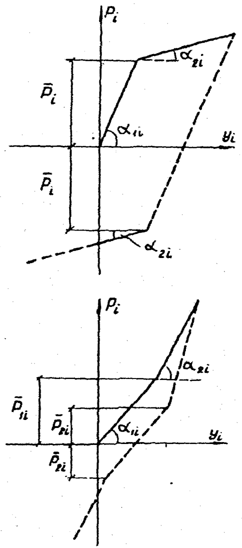

Fig 7

Calculating polylinear diagrams of deformations.