STRENGTH OF REINFORCED CONCRETE COLUMNS IN OBLIQUE SECTIONS EXPOSED TO SEISMIC LOADS

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Severe earthquakes in Anchorage (U.S.A.), Skoplje (Yugoslavia), Tokashi-Oka (Japan), Bucharest (Rumania) and others /1,2,3/ have shown that a great deal of damages in frame buildings occurred due to failure of reinforced concrete columns in oblique sections.

As surveys of damaged and failed structures have demonstrated, methods of assessing column strength based on studies of structures subject to one-way static action of lateral forces, do not provide the required safety of important members when exposed to reversal dynamic (seismic inclusive) loads.

In TsNIISK and NIIZhB there have been tested r.c. specimens simulating the behaviour of columns in frame buildings subject to a simultaneous action of alternating lateral and statically imposed longitudinal forces.

Test specimens were of a rectangular cross-section, 20x30 cm in size, concrete mark 400, with longitudinal reinforcement 4ϕ 25 A-III (μ_a= 0.036) and with transverse reinforcement in the form of tied up stirrups ϕ 6 A-I.

Specimens were made in the form of cantilevers - parts of columns fixed in the base by a massive support. The test set-up was such that specimens could be loaded with a vertical statically acting compressive force and alternating horizontal forces imposed to the free upper edge of the cantilever (Fig.2). The test samples were divided into three group depending on the pattern of imposing the horizontal force.

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The first group included samples tested under a one-way single action of horizontal forces. The group served as a reference one and it assessed the load-bearing capacity of columns in oblique sections under a static transverse load.

The second group was tested under a reversal repeated transverse load of various rate slowly imposed with the coefficient of cycle asymmetry $\rho = -1$. This permitted the influence of such a load on the bearing capacity of members in oblique sections to be determined.

The third group of samples was tested under a dynamic reversal lateral load of various rate with a coefficient of cycle asymmetry of $\rho = -1$ and frequency of 1 Hz, which simulated approximately the action of a seismic load.

The main and most important factor effecting the bearing capacity of members in oblique sections is the amount of transverse reinforcement varied in the tests by the pitch of stirrups. Three typical versions of a stirrup pitch (30, 15 and 7.5 cm) were studied. The maximum pitch u = h (weak transverse reinforcement) conformed with the construction provisions of SNiP II-21-75 for r.c.columns subject to longitudinal compressive forces. The medium pitch u = 0.5h (mean transverse reinforcement) conformed with the constructive provisions of SNiP II-21-75 for r.c. beams subject to transverse forces. The minimum pitch u = 0.25h (strong transverse reinforcement) conformed with constructive recommendations of foreign Codes for columns subject to transverse dynamic (seismic inclusive) loads.

The lateral force was imposed at a distance of l = 3h from the supporting section which is extremely dangerous from the viewpoint of collapse in the oblique section.

The mechanism of the behaviour of samples subject to alternating static and dynamic load with the coefficient of cycle asymmetry of $\rho = -1$ (samples of the second and third groups) can be described as follows.

When a sample is subject to a lateral load of a sufficiently high rate in one direction, normal and oblique cracks form and develop almost in the same way as it has been described earlier for the case of a one-way action of the load. Microcracks and microfailures accompany significant compressive strains in compressed concrete above the oblique crack. Besides as the oblique crack develops along longitudinal reinforcement in the stretched zone break-away cracks occur separating the protecting layer of concrete.

When loading in an opposite way, the above phenomena recur but the direction of oblique cracks and location of the compressed zone are reverse. When the total cycle of loading is completed a system of cross oblique and normal cracks occurs in the sample accompanied with microfailures and break-away cracks near either face of the sample.

When the number of loading cycles is increased, micro-failures and cracks near the faces of the sample develop further and concrete fails to work. The load-bearing capacity of a column depends on the resistance of the core, that is concrete zone within the section restricted by the stirrup, consisting of concrete blocks formed by cross oblique cracks and bound by longitudinal reinforcement and stirrups (Fig.1,b). At loading and unloading, displacement of blocks as regards each other along and across cracks takes place thus causing the break of cohesion between blocks and destruction of blocks. The core loses its capacity to resist as a whole the acting forces and so the member collapses.

The effect of alternating and repeated loading depends greatly upon the pitch of stirrups that determines the behaviour of the central portion of the member as a whole. With a small stirrup pitch that effect on strength in the oblique section is not great. But with the rise of the stirrup pitch, the negative effect of the reversal load increases resulting in a relative reduction of both the level of the limit lateral force and maximum number of cycles which the member can take up under the given level of loading (see Table 1).

Besides, the negative influence of the reversal load can be seen quite clearly when there is no compressive longitudinal force. For instance, with $N = 0$ a sample with weak stirrups withstood 2 cycles, whilst a sample with a longitudinal compressive stress of 400 KN and the same stirrup pitch withstood 45 cycles under the same level of loading by a lateral force.

Strains of longitudinal reinforcement and of stirrups and deflections of test members as well increase essentially under the effect of reversal loads, which means that their rigidity reduces.

The total amount of strains and deflections with failure in oblique sections appears, however, to be smaller than with failure in normal sections which is associated with the yield of reinforcement. The pattern of failure of members in oblique sections is fairly brittle.

The new method of calculation devised at the Central Laboratory of Reinforced Concrete Theory (NIIZhB) 5 can be used to calculate strength of columns in oblique sections under a single loading. According to the method, the limit lateral force Q is obtained from the equation of equilibrium of lateral forces in the oblique section.

$$Q = Q_x + Q_{\delta_1} + Q_{a \cdot 3} \qquad (1)$$

where Q_x is the lateral force taken up by transverse reinforcement in the oblique crack;

$Q_{\delta 1}$-is the lateral force taken up by concrete above the oblique crack;

$Q_{a.3} = Q_{\delta 2}$ - is the lateral force taken up by dowel stresses in longitudinal reinforcement intersecting the oblique crack, and by cohesion forces in the oblique crack.

The longitudinal force and compressed reinforcement are added to the design formulae. As the analysis have shown, the calculated results are in good agreement with the test data.

When calculating strength of oblique sections for reversal loading by the new method it would be reasonable to take into account the work of the section core only within the stirrups, reducing or eliminating the $Q_{\delta 1}$, value taken up by concrete above the oblique crack and $Q_{a.3} = Q_{\delta 2}$ taken up by the dowel force in longitudinal reinforcement and by cohesion forces in the oblique crack.

The above said can be expressed by the following relationship

$$Q = Q_x + \omega (Q_{\delta 1} + Q_{a.3}) \quad (2)$$

Basing on the analysis of the test data, the value of the ω coefficient can be assumed as a first approximation depending on the stirrup pitch u with respect to the height h of the section of the member as follows

$$\omega = 1 - 0{,}5 \frac{u}{h} \quad (3)$$

In addition to the existing requirements it is necessary to restrict the stirrup pitch $u \leq 0.5h$ and diameter of stirrups $d_x \geq 8$mm in reinforced concrete buildings subject to momentary reversal repeated horizontal loads, seismic ones inclusive. The restriction, a bit too conservative, is quite important in securing safety of columns, since the available design methods for such effects are rather conditional both with regard to loads (taking into account a complicated nature of their action and difficulties in presenting it in an analytical form simple for calculations) and rigidity characteristics of r.c. structures under such actions.

Until the new method is finally approved in pilot designs, the technique given in SNiP II-21-75 can be used with due account of the reduction of the limit lateral force Q_δ taken up by concrete of the compressed zone by the value ω assumed equal to about 0.75, relevant to a maximum permissible stirrup pitch.

The reduction of the effective height assumed within the section core, is allowed for by introducing the coefficient of 0.85.

As a result, the load-bearing capacity in the most disadvantageous oblique section will be expressed by the relationship:

$$Q_{x\delta} = 2\sqrt{R_p b h_0^2 q_x} \quad (4)$$

which is rather a conservative assessment.

CONCLUSIONS SND SUGGESTIONS

1. The conducted tests have indicated that when a reinforced concrete member is subject to a reversal dynamic (such as a seismic one) transverse load damages are being accumulated as loading cycles repeat, thus loading to a reduction in load-bearing capacity in oblique sections as compared to a single static action of a lateral load. The magnitude of the reduction depends upon the amount of transverse reinforcement.

2. The comparison of the results of reversal tests under repeated static and dynamic loads have shown that on the average they are in good agreement. Tests under a static repeated reversal load may, therefore, serve as a fairly reliable criterion for assessing the influence of a dynamic action of the load within the investigated frequency range.

3. The presence of a compressive longitudinal force within the range of $N = 0{,}2\text{-}0{,}5 R_{np} b h_0$ increases essentially the bearing capacity of elements in oblique sections both under a single static and reversal static and dynamic action of the lateral load. With the increase of the number of cycles the effect of strength growth in the oblique section associated with the positive influence of the compressive longitudinal force, reduces.

4. An analytical method for calculation of strength of elements in oblique section has been devised basing on a combined use of equations of equilibrium of limit stresses (moments, lateral and longitudinal forces) and taking account of the reversal repeated action of the load.

5. The coefficient of working conditions for r.c. elements subject to a dynamic reversal lateral load (static, wind, etc.) should be taken less than unity in calculations of strength in oblique sections. Special complementary constructive restrictions should be introduced for transverse reinforcement as compared to a one-way static action of the load.

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Table 1

Results of testing column samples subject to reversal static and dynamic load

Sample code	Stirrup pitch u cm	Longitudinal compressive force N kN	Crushing static lateral load Q_p^{on} kN	Static and dynamic lateral reversal load $Q_1=Q_2$ kN	Number of cycles n
КД -Ш-I КС-У-4 КД-УП-2		0	I00	90 (0,9 Q_p^{on}) 80 (0,8 Q_p^{on})	7 2 22
КД-УШ-3 КС-У-5 КД-УШ-2	30 ($u=h$)	($0,2 R_{np} b h_0$) 400	I40	I26 (0,9 Q_p^{on}) II2 (0,8 Q_p^{on})	28 45 67
КД-УШ-5 КД-УШ-6 КС-У-6		($0,5 R_{np} b h_0$) 900	I60	I44 (0,9 Q_p^{on}) I28 (0,8 Q_p^{on})	9 64 69
КД-УI-4 КД-УI-5 КС-УI-I		0	I20	I08 (0,9 Q_p^{on}) 96 (0,8 Q_p^{on})	32 II4 9
КД-I-4 КД-УI-6	I5	400	I70	I53 (0,9 Q_p^{on})	67

КД-УП-I КС-УI-2	($u=0{,}5h$)	$(0{,}2R_{пр}bh_0)$		I38 $(0{,}9\,Q_p^{оп})$	I26 I00
КД-УП-2 КД-УП-3 КС-УI-3		900 $(0{,}5R_{пр}bh_0)$	I90	I69 $(0{,}9\,Q_p^{оп})$ I52 $(0{,}8\,Q_p^{оп})$	38 I36 64
КД-IУ-3 КД-IУ-4 КС-Ш-4		0	I50	I35 $(0{,}9\,Q_p^{оп})$ I20 $(0{,}8\,Q_p^{оп})$	26 II6 49
КД-УП-4 КД-УП-5 КС-Ш-5	7,5 ($u=0{,}25h$)	400 $(0{,}2R_{пр}bh_0)$	I70	I53 $(0{,}9\,Q_p^{оп})$ I36 $(0{,}8\,Q_p^{оп})$	74 480 I00
КД-IУ-4 КС-IУ-2 КД-IУ-5 КС-IУ-3		500 $(0{,}5R_{пр}bh_0)$	200	I80 $(0{,}9\,Q_p^{оп})$ I60 $(0{,}8\,Q_p^{оп})$	52 26 2I6 I00

Note:

КС - columns tested under a static reversal load

КД - columns tested under a dynamic reversal load

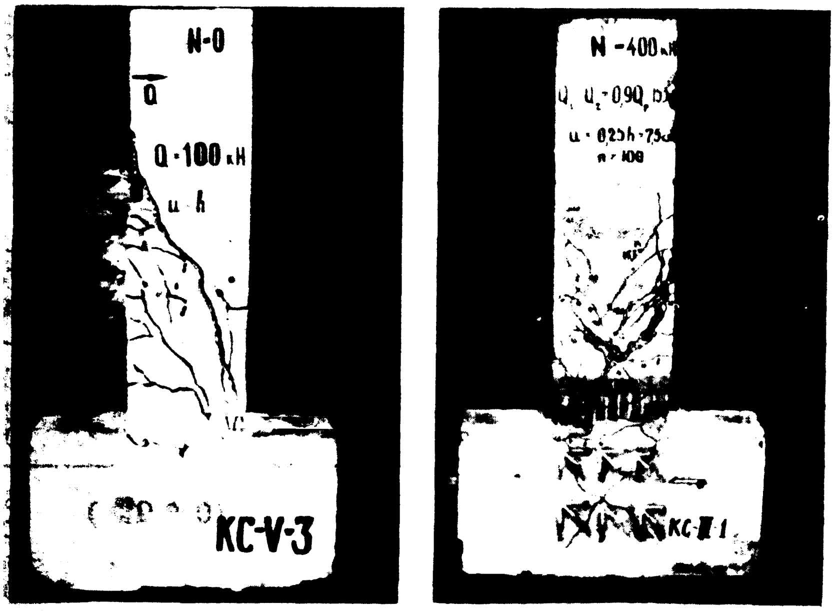

Fig.1. Sample after being subject to a lateral load.
a) one-way static load, b) reversal static load.

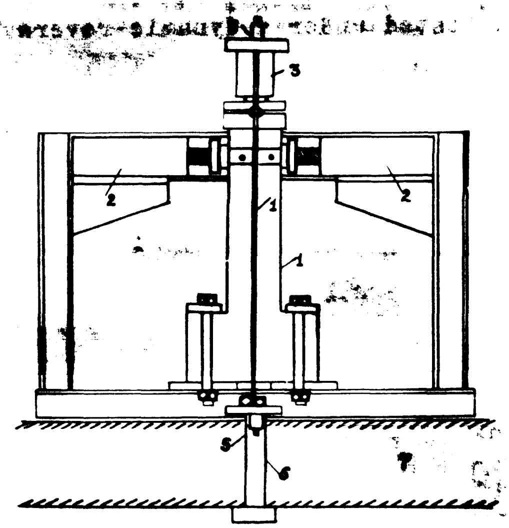

Fig.2. Scheme of plant for tert of column fragments on signvariable dynamic loads.
1. test specimen; 2. pulsating jacks; 3. static lask; 4. thrusts for tranafer the vertical static load; 5. clamps; 6. anchor bolt; 7. pomer floor.