*The object of this research was the crack resistance of inclined sections of concrete and reinforced concrete fragments of protective structures under the action of emergency dynamic loads. The characteristics of dangerous emergency dynamic loads on protective structures (seismic, aircraft attack), the experience of increasing the crack resistance of inclined sections with various materials and design measures under static effects have been described. Areas of influence of dynamic loads on reinforced concrete structures reinforced with horizontal grids near the upper and lower faces need to increase crack resistance and eliminate the risk of splitting in the mesh plane. Comparison of the results of experimental studies of inclined sections of protective structures in the area of influence of local emergency load showed the feasibility of such structural measures. Additional horizontal reinforcement near the pushing face increases crack resistance by 55–65 %. When using the developed theoretical dependences, the error in determining the cracking forces and pushing strength does not exceed 20.7 %.*

*Increased crack resistance is ensured by limiting the maximum diameters of the rods of horizontal grids and their pitch. Especially important is the arrangement of additional reinforcement in the middle zone, taking into account the actual tensile strength of concrete in the calculated dependences. Complete elimination of the danger of splitting in areas of probable action of emergency dynamic load in protective structures in the planes of the grids is recommended through the use of concrete of class not lower than C16/20, the use of reinforcement Ø12–14 mm. The optimal pitch of the rods is 50–125 mm. This makes it possible to increase the reliability of the design and operation of protective structures in case of emergency impacts, to reduce the cost of their repair after such impacts*

*Keywords: protective structure, airplane crash, push angle, horizontal reinforcement, crack resistance of sections, nagel effect*

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# IMPROVING THE CRACK RESISTANCE OF INCLINED CROSS-SECTIONS OF REINFORCED CONCRETE CONTAINMENT SHELLS IN AREAS OF EMERGENCY LOADS OF PUSHING

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## 1. Introduction

Emergency dynamic loads (seismic, hydrodynamic, aircraft crash, shock wave, etc.) and their impact on reinforced concrete protective structures have been studied for a long time. Such loads are very dangerous since their incorrect consideration leads to accidents, numerous human casualties, and loss of material values. Their local action can lead to the onset of a boundary state in inclined sections on the cut when pushing. The angle of formation of a critical crack depends on the speed of application of this load. For seismic effects on floor slabs in the zone of pushing them by columns, the characteristics of the vertical component of the load are important, which can be determined by knowing the speed of the horizontal component. The cut force in the support cross-sections of individual structural elements can be determined using the coefficient $a$ – acceleration in fractions from the acceleration of gravity $g$. The characteristics of the dynamic load from the fall of aircraft and their parts are constantly changing due to various causes of accidents (hostilities, equipment failures, terrorist attacks, etc.). The number of such important structures with protective elements is also constantly increasing, including the variety of their design solutions. The probability of such impacts on protective structures has increased significantly, and the bearing capacity of protective structures in pushing areas with angles less than 45° is not well understood. This is also very important, given that the chipping strength of concrete, on which the crack resistance of inclined sections depends, much lower than the compressive and fracture strength along inclined sections, is more dangerous. Therefore, it is important to have more experimental research results to assess the impact of emergency dynamic loads more accurately on inclined sections of protective plates and shells. This will in practice reduce the risk of inadmissible inclined cracks, overtime deformations, and destruction of structures with serious consequences.

## 2. Literature review and problem statement

The speed of the horizontal component of seismic waves has recently been widely described for many sources of earthquakes. In works [1, 2], the equations for calculating the vertical component of the speeds of movement of soil particles are described on the example of earthquakes, including with the epicenters of shallow occurrence. The relationship between the vertical and horizontal components of velocities has been studied in detail. The issues of the influence of the vertical component of seismic waves on the structures of buildings have not been considered, including the pushing of floors by vertical structures, since a limited amount of data did not make it possible to draw reasonable conclusions on this issue. In [3], the results of more than 300 earthquakes are analyzed to compile a new, more accurate model of vertical seismic loads. The model is proposed for strong earthquakes with a magnitude of 7.0–8.5 and maximum distances of up to 300 km from the epicenter. The insufficiency of the database did not make it possible to consider earthquakes with a magnitude of 8.5–9.0, in which maximum vertical dynamic loads and minimum pushing angles of less than 40° occur. In [4, 5], the magnitude and distance to the epicenter are limited even more (up to 8.0 and up to 200 km). These models make it possible to clarify the ratio between the vertical and horizontal components of the speeds of dynamic seismic load for the described sources of European and Middle Eastern earthquakes. The high predictability of models compared to others using peak soil acceleration is their advantage. But, for use in regulatory documents for the calculation of structures, it is necessary to take into account precisely the peak loads when determining the pushing forces. This restrains the construction standardization of such parameters and makes it impossible to use in the calculations for pushing. The prediction of the speeds of applying the vertical component of the dynamic load based on the study of earthquakes in Japan and Iran is addressed in [6, 7]. In them, based on empirical models, the maximum vertical velocities are calculated taking into account the spatial correlation. It also makes it possible to clarify the ratio between the horizontal and vertical components of the emergency dynamic load and more accurately determine the maximum loads. Increasing the amount of analyzed data and, accordingly, the accuracy of forecasting, is possible through the use of synthesized accelerograms. In this direction, it is necessary to accelerate the research. In national norms, this ratio is determined by a coefficient of 0.7, which for some extreme cases may be underestimated. The clarification of this ratio is also restrained by the lack of analysis of large arrays of earthquake accelerograms. The lack of state funding for such studies does not make it possible to clarify the normalized indicators of the vertical components of seismic loads. All this suggests that conducting studies of crack resistance of reinforced concrete structures of protective structures will eliminate existing gaps, increase their operational characteristics, reduce the consequences of emergency effects and repair costs.

Special requirements for the design of inclined sections of monolithic rigid assemblies of connections of columns and crossbars apply to support areas with a length of two cross-sections of a crossbar or column. In these areas, the maximum pitch of vertical knitted clamps should not exceed 150 mm, and the pitch of nets or individual rods in the middle zone of the node should not exceed 100 mm. The strength of inclined sections on the cut using multi-row horizontal reinforcement in beams and thick slabs is well studied [8]. But the studies are limited to cut spans at fracture angles of 45–63.4°, which corresponds to static loads, but not dynamic. Calculation for cutting at local pushing at angles less than 45° according to the national standard DSTU B V.2.6-156-2010. To be limited: the calculated cross-sectional height must be larger than the size of the external load. In the EU, this issue is normalized by Eurocode 2 (Design of Concrete Structure. EN 1992 – 1.1 General Rules and Rules for buildings). This leads to errors when used to determine the bearing capacity of thin plates and shells. Also, dependences do not take into account horizontal reinforcement due to lack of experimental data. For plates and shells with a thickness of less than 200 mm, a technique for calculating the strength developed at the Research Institute of Building Structures (NDIBK, Kyiv) with the arrangement of a horizontal grid in the middle of the cross-sectional height was used [9]. When applying horizontal rods, the effectiveness of such reinforcement is explained by the use of the nagel effect. When developing the estimation hypothesis, it was accepted that the plastic properties of concrete are sufficient for the bearing capacity of the push zone (similar to the method of the current norms) determined by the sum of the bearing capacity of concrete and reinforcement. When assessing the contribution of reinforcement to the strength of inclined section on the cut, it was accepted that the plastic properties of the materials are sufficient to realize the pressure of concrete on the reinforcing rod, close to rectangular. The bending moment along the length of the reinforcing rod was determined by its plastic resistance torque $W_{pl}$ and the calculated resistance of the reinforcement $f_{yd}$ for the rod's given Ø. Additional reinforcement was recommended to be placed in the middle of the cross-sectional height. The minimum required lengths at the rod beyond the limits of the action of the pushing force is recommended to be determined from the condition of ensuring its anchoring.

This technique for static loads theoretically substantiates and does not recommend taking into account the fittings for pushing, placed at other levels in terms of the cross-sectional height of the structure. Therefore, the study while placing horizontal grids in two levels was not carried out and the effect of additional horizontal grids on the strength of inclined sections during pushing has not been investigated, which confirms the need for such studies.

The effect of an emergency dynamic load on the protective structure against an aircraft crash can lead to local pushing of the plate or shell with an angle of destruction of less than 45° [10]. Many research results have been published for cases of accidents of various aircraft, both civilian and military. In [11], the results of dynamic tests for the effect of emergency load are given. Such dynamic tests are complex, potentially dangerous, and, at the same time, it is impossible to reliably establish the nature of the evolution of cracking. It is more expedient to conduct static tests with certain angles of destruction. Works [12, 13] report studying the protective structures of nuclear power plants for the action of an emergency load (accident or attack of an aircraft). The characteristics of the load (dependence of energy on the mass of the incident body, etc.) were studied. The estimation methods established the parameters for increasing the intensity of deformations of concrete structures in the critical zone from 1.4 to 4.9 times in nonlinear analysis compared to linear. Emphasis is on increasing the thickness of the protection, in which no other damage, except cracks, occurs. The impact of reinforcement of the protective structure is not assessed, which significantly increases the risks of splitting and the cost of restoring the integrity of the structure after impact. It is indicated that the criteria for damage to a concrete structure according to the NDRC standard are more conservative and inaccurate compared to nonlinear detailed analysis. At the same time, the critical use of steel reinforcement, the plastic properties of which provide the advantages of reinforced concrete, is also not explored. Earlier, it was found that the magnitude of the angle of destruction does not depend on the kinetic energy of the load but on the speed of its application. Thus, in the event of an accident of a military aircraft with the parameters of the surface area of its contact with a shell of 7–14 $m^2$, weighing 2.0 tons and a speed of 215 m/s. The same kinetic energy has a body weighing about 150 kg, falling at a speed of 800 m/s. The angle of pushing $\gamma$ at the same time decreases from 40° (for the corresponding load rate $v$=2.5·10$^4$ kN/m$^2$s) to about 34°. This approach is implemented in the development of hypotheses [14, 15]. The estimation hypotheses for determining the bearing capacity are based on the prediction of the simultaneous achievement of the limit state from the action of tensile and chipping stresses, evenly distributed over the cross-sectional area (on normal and tangential sites in the plane of destruction). The mathematical model of such a load in the calculation of strength is taken in the form of elastic-viscous or elastic-viscoplastic systems, the reaction of which, when interacting with a protective reinforced concrete shell, determines the dynamic emergency load. In one of the approaches to solving this problem, the system of equations of shell motion under the action of this load and the piecewise-linear integral equation of the first kind using the initial conditions and conditions of the d'Alembert is considered. The corresponding force component of the emergency load [14, 15] is calculated by the method of integral Laplace transformation, taking into account the ratio of the stiffness of the protective plate or shell and the design of the aircraft. The proposed estimation dependences take into account the presence of only vertical clamps and the dynamic increase in the strength of inclined sections with the corresponding coefficients to the static load. This makes it possible to conduct static tests and, according to their results, predict the dynamic strength of the structure in the zone of local pushing. But when applying horizontal reinforcement leads to significant errors in determining the bearing capacity since it does not take into account the peculiarities of the operation of horizontal reinforcement. This also confirms the need for experimental study of the operation of inclined sections in the pushing zone when placing horizontal reinforcement in several levels in terms of sample height. The push zone was shaped like a cut cone.

The transverse reinforcement coefficient for the case of vertical clamps $k_w$ was taken equal to 1.4, if any, and 1.0 in the absence, and the dynamism coefficient is accepted as 1.4. The use of such integral coefficients can lead to significant errors in calculating the strength and crack resistance of sections of reinforced concrete protective structures. This allows static tests to be carried out and brought to dynamic ones but the coefficients of influence of horizontal reinforcement on certain ones were not defined.

The adopted estimation scheme under the action of an emergency dynamic pushing load differs from the scheme for static loads accepted in the current standards. They use the concept of control perimeters, the first of which is located at a distance of $2d$ ($d$ is the working cross-sectional height) from the zero perimeter, or the limit of applying an external load. At the same time, the angle of destruction $\gamma$=90–$\Theta$=63.4°. For reinforcement of pushing areas at pushing angles $\Theta\geq$arctan(½) for plates with a thickness of more than 200 mm, it is recommended to use vertical clamps and bends. It is also recommended to include a bend outside the area of the external load in the calculation if the distance from it to the edge of the load $\leq$0.25$d$.

The operation of the transverse reinforcement of clamps, normal to the longitudinal axis of a thin plate or shell, is complicated by the insufficient length of anchoring of the clamps. The adhesion of reinforcement to concrete is also insufficient. Additional longitudinal rods at the level of the lower and especially upper reinforcing meshes make concreting difficult. The "burning" of rods of small diameter is likely.

The use of clamps as part of additional frames made in the factory using contact welding leads to the need to use studs or individual rods with special washers at the ends, which is technologically complex.

When arranging bends of horizontal reinforcement of nets or inclined clamps within the push zone, the place of application of the emergency load is unknown. Therefore, the place and other geometric parameters for the device of bends or clamps become very indistinguishable due to the need to take into account the structural radii of the bend of the rods (with indefinite angles of intersection with the surface of the pushing prism). This is especially felt for plates and shells less than 300–400 mm thick.

Other design measures and materials are also used to strengthen inclined sections, including steel and non-metallic fiber [16, 17], carbon cloths, reinforced concrete clips, etc. These techniques are also used to further increase the calculated strength of concrete of protective structures for stretching when they are strengthened but are not advisable in the construction of such structures.

According to the results of the review of the state of studies into the strength of inclined sections under various emergency loads on protective structures, the following conclusions can be drawn:

– there are several calculation procedures, designing techniques, and reinforcing cross-sections, which do not describe the nature of destruction under dynamic emergency loads of inclined sections reinforced with horizontal grids;

– the accuracy of many approaches and solutions to determine the bearing capacity and strengthen inclined sections in case of emergency impacts remains uncertain;

– in thin slabs and shells, the installation of additional vertical clamps and bends is technologically complex and does not lead to a significant increase in the bearing capacity for pushing.

## 3. The aim and objectives of the study

The aim of this study is to develop structural measures to increase the crack resistance of sections of reinforced concrete slabs and shells of protective structures in the zone of pushing by emergency dynamic load. This will make it possible to significantly increase the crack resistance of sections in the push zone, improve the manufacturability of concreting, eliminate the risk of destruction from splitting in the mesh plane.

To accomplish the aim, the following tasks have been set:

– to conduct experimental studies of samples – fragments of a monolithic shell of a protective structure with horizontal reinforcement at different levels in cross-sectional height at two angles of pushing and establish the influence of the angle and its changes on the strength of crack resistance of inclined sections;

– to propose, based on the accepted hypothesis, theoretical dependences for calculations for pushing reinforced concrete protective structures with multi-level horizontal grids with emergency dynamic load, to assess the convergence of calculations and the results of experimental studies.

## 4. The study materials and methods

The object of this study was the crack resistance of reinforced concrete protective structures in areas affected by local emergency dynamic pushing load.

The main hypothesis is one that makes it possible, according to the results of static tests of the protective structure, to evaluate its operation under dynamic loads.

Additionally, in the pushing zone at fracture angles of less than 45°, it is more expedient to use horizontal grids installed at optimal levels in terms of the cross-sectional height of the structure. This will make it possible to use the nagel effect of reinforcement to increase crack resistance and pushing strength. Conducting experimental studies will make it possible to more accurately take into account the effect of horizontal reinforcement. Based on the accepted hypothesis and the results of experiments, it is possible to propose theoretical dependences that take into account the features of the reinforcement of the push zone and offer structural solutions to increase the crack resistance of this zone.

Generalization of world experience in studying the amplitude of velocities (Fig. 1) [18] shows that it is mainly in the range of 0.10–1.0 m/s for the intensity of earthquakes of 6–9 points, for which an appropriate calculation is required.

For an intensity of 7–9 points (see the selected section of velocity grams in Fig. 1), speeds of more than 5 m/s are recorded, corresponding to maximum accelerations of 0.45–0.5 from the acceleration of gravity *g*. At such speeds, possible angles of destruction are less than 45°. In the study of inclined cross-sections on the action of dynamic seismic loads, it was found that the ratio of the cut span to the working height of the cross-section can be taken as 1.0 (the selected angles of the destroying cracks in Fig. 2) [18] but, at the highest recorded speeds, it will be smaller.

Therefore, in experimental studies of inclined cross-sections under the action of an emergency local pushing load, work of reinforced concrete and concrete models was studied – fragments of thin slabs or shells at angles less than 45°. Pushing force $F_{Ed}$ (Fig. 3) was applied perpendicular to the sample surface on a round area with a diameter of 250 mm, which corresponded to the estimation static model of emergency dynamic load [10].

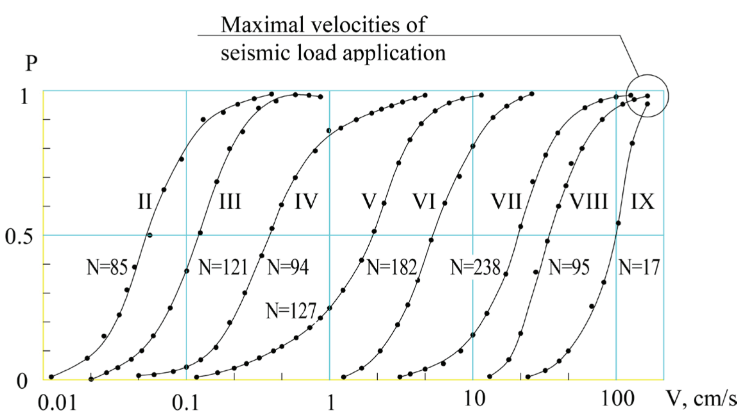


Fig. 1. Distribution of amplitudes of velocities for earthquakes with intensity II–IX points according to world data: P – probability, N – volume of data used [18]

Concrete cubes installed around the perimeter of the sample modeled the resistance distributed along the perimeter of the circle at a distance of ≈135 mm from the limit of load application. The fracture angle γ was close to 40° at the accepted sample thickness *d*, which was 160 mm (3-1...3-12) and up to 34° at a thickness of 200 mm (3-13...3-24) in the samples of the second series. The partial effect of the clip was achieved by reinforcement of Ø12 class A240 at the ends of working rods of the nets in the form of a ring. This reinforcement also provided anchoring of working rods of the nets. The load was applied in stages with an exposure of 7...15 minutes to monitor the condition of the samples, record readings of measuring instruments, measure the width of crack opening. The research was conducted on static loads, i.e. the dynamic coefficient $k_d$ was equal to 1.0. The class A400C working fittings with $f_{yd}$=364 MPa of periodic profile ∅12 (10 samples), ∅16 (9 samples) (Fig. 4, 5) were used in the form of one or two flat welded meshes. The mesh was installed in the middle of the height of the sample, with two meshes, one of them was installed near the face to which the pressing force was applied.

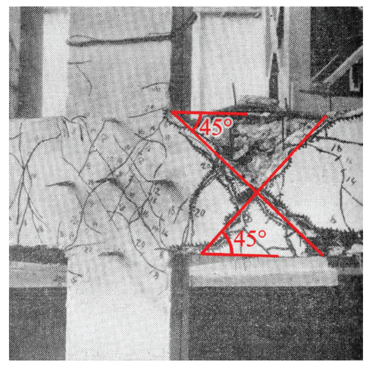


Fig. 2. Destruction at the support section of the assembly of a monolithic frame reinforced with horizontal grids [19]

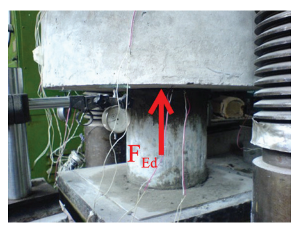


Fig. 3. Sample prepared for testing

A total of 24 (2 series) round reinforced concrete and concrete fragments of Ø700 mm were tested. Reinforcing rods with an area *of* $A_{sh}$ were taken into account for pushing (Table 1), which were located in the middle and beyond the limit at a distance of no more than 0.25*d* from the zero perimeter (perimeter of the area of action of the push force). The estimation area of the cut cone *A* [10] was determined from the condition

$$A=\pi AB\cdot(a+\mathrm{AB}\cdot\sin\gamma), \qquad (1)$$

where *a* is the diameter of the area of application of the load;

γ – the angle of destruction during pushing;

*AB* – the length of the cut cone generatrix.

Samples C-5, C-6, C-8, C-17, C-24 were tested without additional horizontal reinforcement. The tensile strength of concrete $f_{ctm}$ (Table 1) was determined by splitting standard cubes. It also shows the geometrical parameters and characteristics of concrete and the reinforcement of samples.

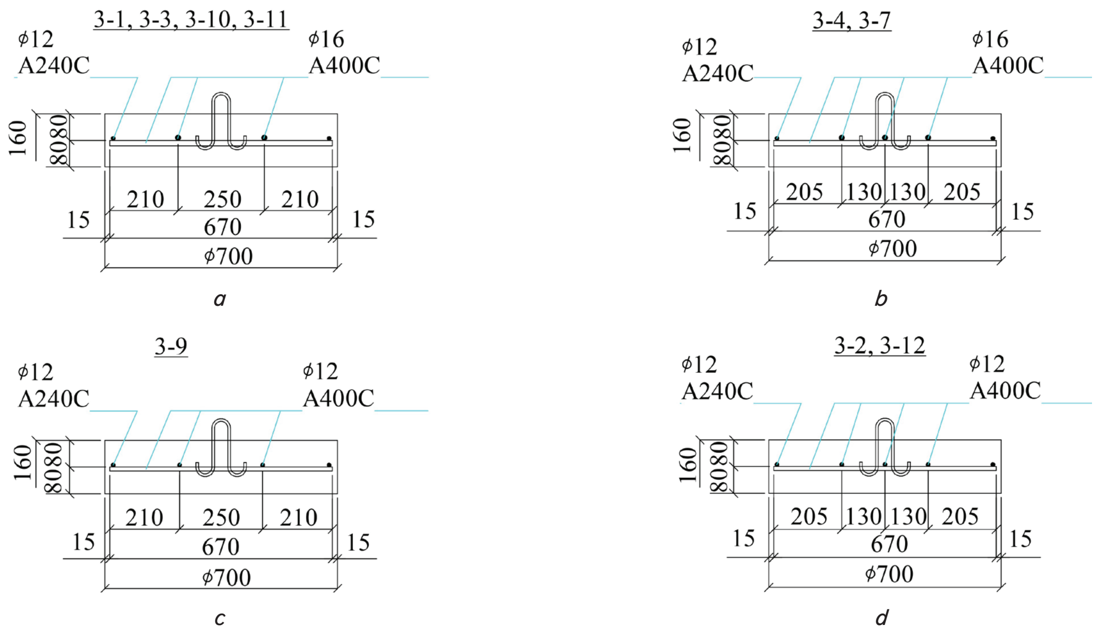


Fig. 4. Reinforcement of samples of the first series: *a* – mesh C-1; *b* – mesh C-2; *c* – mesh C-3; *d* – mesh C-4

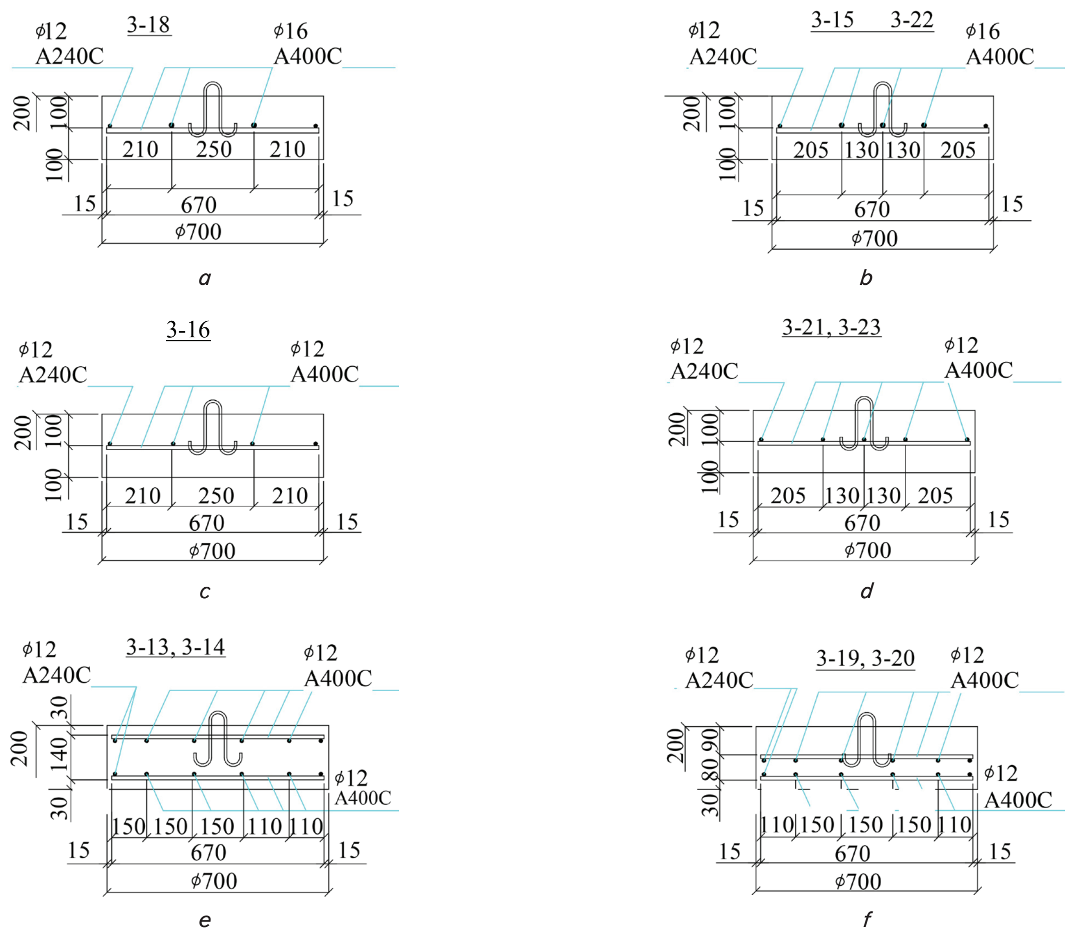


Fig. 5. Reinforcement of samples of the second series:
*a* – mesh C-1; *b* – mesh C-2; *c* – mesh C-3; *d* – mesh C-4; *e, f* – meshes C-5

The distance, given in Table 1, to the upper face $d_1$ from the axis of the lower grids and $d_2$ from the axis of the upper meshes of the samples were measured after their destruction. To control the deflections of the samples during the test, 4 clock-type indicators were installed with a division price of 0.01 mm, located on two mutually perpendicular diameters at a distance of 50 mm from the edge of the sample. Deformations of concrete on the stretched face were measured by strainers based on 50 mm; the width of the opening of cracks on the side and upper faces – with the MPB-3 microscope.

Table 1

Characteristics of concrete and sample reinforcement

| Designation of the sample | $f_{cd}$, MPa | Tensile strength of concrete, MPa | | | | The diameter of the reinforcement Ø, mm | Number of rods, m from [9] | $d_1/d_1$, mm | $A_{sh}$, cm$^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $R_{bt}$, from [20] | $f_{ctk,0.05}$, from [20] | $f_{ctm}$, experiment | $f_{ctm}$, from [20] | | | | |
| 3-1 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 8 | 80/– | 16.08 |
| 3-2 | 11.5 | 0.90 | 1.30 | 0.36 | 1.90 | 12 | 12 | 80/– | 13.57 |
| 3-3 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 8 | 80/– | 16.08 |
| 3-4 | 11.5 | 0.90 | 1.30 | 0.36 | 1.90 | 16 | 12 | 80/– | 24.12 |
| 3-5 | 11.5 | 0.90 | 1.30 | 0.36 | 1.90 | – | – | – | – |
| 3-6 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | – | – | – | – |
| 3-7 | 11.5 | 0.90 | 1.30 | 0.36 | 1.90 | 16 | 12 | 68/– | 24.12 |
| 3-8 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | – | – | – | – |
| 3-9 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 12 | 8 | 66/– | 9.05 |
| 3-10 | 11.5 | 0.90 | 1.30 | 0.36 | 1.90 | 16 | 8 | 65/– | 16.08 |
| 3-11 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 8 | 60/– | 16.08 |
| 3-12 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 12 | 12 | 70/– | 13.57 |
| 3-13 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | 12 | 24 | 42/158 | 27.14 |
| 3-14 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | 12 | 24 | 15/126 | 27.14 |
| 3-15 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 12 | 100/– | 24.12 |
| 3-16 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | 12 | 8 | 100/– | 9.05 |
| 3-17 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | – | – | – | – |
| 3-18 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 8 | 98/– | 16.08 |
| 3-19 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | 12 | 16 | 34/90 | 18.10 |
| 3-20 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | 12 | 16 | 42/98 | 18.10 |
| 3-21 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 12 | 12 | 80/– | 13.57 |
| 3-22 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 16 | 12 | 100/– | 24.12 |
| 3-23 | 7.5 | 0.66 | 0.80 | 0.17 | 1.20 | 12 | 12 | 100/– | 13.57 |
| 3-24 | 8.5 | 0.75 | 0.90 | 0.21 | 1.60 | – | – | – | – |

## 5. Results of studies of inclined cross-sections when pushing by an emergency load

### 5. 1. The results of experimental research

As a result of our experimental studies, the load of destruction along inclined and normal cross-sections was determined. Concrete samples were destroyed during the formation of normal cracks from the action of the bending moment (force $F^n_{crc}$).

In the reinforced samples (Table 3), at the following steps there were through annular spatial cracks along the lateral surface of the pushing cone (force $F^v_{crc}$), which caused the destruction of inclined cross-sections from normal and tangential stresses (Fig. 6).

In some samples, vertical and in some also horizontal cracks in the middle of the height (force $F^h_{crc}$) were formed on the side surface during destruction, which indicated the destruction of concrete for splitting in the reinforcement mesh plane (Fig. 6, *b*). Such destruction was recorded in samples of the concrete of class C10/12 and with insufficient adhesion of reinforcement to concrete.

Table 2

Destructive compressive forces and bending moments in concrete samples

| Sample designation | $W_{pl}$, cm$^3$ | Destructive forces | |
|---|---|---|---|
| | | $M_{Edu}$, kNm | $F_{Edu}$, kN |
| 3-5 | 4,843 | 7.332 | 91.53 |
| 3-6 | 4,843 | 3.661 | 45.81 |
| 3-8 | 4,843 | 3.488 | 44.15 |
| 3-17 | 8,000 | 8.374 | 104.67 |
| 3-24 | 8,000 | 11.505 | 143.81 |


*a* *b*

Fig. 6. Destructive cracks: *a* – on the upper face; *b* – on the side face

Table 3

Experimental destruction efforts and characteristics of reinforced samples

| Sample designation | $F_{Edu}$, kN | $f_{ck}$, MPa | $C_{Rdc}$, kN | $\rho_1$ | $F^n_{crc}$, kN | $F^v_{crc}$, kN | $F^h_{crc}$, kN |
|---|---|---|---|---|---|---|---|
| 3-1 | 104.67 | 12.0 | 0.801 | 0.0065 | 52.29 | 65.43 | – |
| 3-2 | 222.29 | 20.0 | 0.95 | 0.0055 | 91.53 | 183.2 | – |
| 3-3 | 104.67 | 12.0 | 0.801 | 0.0065 | 52.29 | 59.35 | – |
| 3-4 | 346.59 | 20.0 | 0.95 | 0.0098 | 104.61 | 183.07 | 346.59 |
| 3-7 | 281.15 | 20.0 | 0.95 | 0.0098 | 104.7 | 209.23 | 281.15 |
| 3-9 | 71.91 | 12.0 | 0.801 | 0.0037 | 39.24 | 65.43 | – |
| 3-10 | 156.96 | 20.0 | 0.95 | 0.0065 | 39.24 | 156.92 | – |
| 3-11 | 71.91 | 20.0 | 0.95 | 0.0065 | 26.19 | 65.43 | – |
| 3-12 | 91.53 | 20.0 | 0.95 | 0.0055 | 39.24 | 78.46 | – |
| 3-13 | 294.3 | 15.0 | 0.863 | 0.0088 | 78.48 | 183.2 | 294.3 |
| 3-14 | 170.01 | 15.0 | 0.863 | 0.0088 | 78.48 | 104.7 | – |
| 3-15 | 130.77 | 12.0 | 0.801 | 0.0078 | 52.31 | 78.48 | – |
| 3-16 | 143.91 | 15.0 | 0.863 | 0.0029 | 78.48 | 130.77 | – |
| 3-18 | 130.77 | 12.0 | 0.801 | 0.0052 | 65.43 | 78.48 | – |
| 3-19 | 209.25 | 15.0 | 0.863 | 0.0059 | 78.49 | 104.61 | – |
| 3-20 | 235.44 | 15.0 | 0.863 | 0.0059 | 78.49 | 130.77 | – |
| 3-21 | 156.96 | 12.0 | 0.801 | 0.0088 | 65.43 | 104.6 | 156.96 |
| 3-22 | 150.39 | 12.0 | 0.801 | 0.0078 | 52.32 | 78.48 | – |
| 3-23 | 156.96 | 12.0 | 0.801 | 0.0044 | 65.38 | 104.61 | – |

**5. 2. Proposals for calculation and comparison with experimental results**

The bearing capacity of horizontal reinforcement when calculating inclined cross-sections for a cut during pushing was calculated by dependence [9]:

$$F^h_{sw} = 0.576m\sqrt{f_{yd}g\varnothing^3}, \qquad (2)$$

where $m$ is the number of rods in the push zone;

$f_{yd}$ – calculated material resistance of reinforcing rods;

Ø – diameter of reinforcing rods in the pushing zone;

$g$ – the smallest of the three values of strength: when bending the rod, crushing concrete, pulling out the reinforcement.

The experimental destructive effort was also compared with the calculated ones according to the current standards: the concentrated resistance force on inclined cross-sections $F_{Rdu}$. The concentrated resistance force on the inclined cross-sections (the case of local load action) was determined by dependence:

$$F_{Rdu} = A_{c0}f_{cd}\left(A_{c1}/A_{c0}\right)^{1/2} \le 3.0 f_{cd}A_{c0}, \qquad (3)$$

where $A_{c0}$=0.049 m$^2$ is the load area;

$A_{c1}$=0.212 m$^2$ – the maximum estimated distribution area;

$f_{cd}$ – compressive strength of concrete.

A comparison of the experimental destructive forces of concrete samples with those calculated according to (3) is given in Table 4. For concrete samples without reinforcement, the theoretical moments were calculated according to the dependence: $M_{Rd}=f_{ctk,0.05}W_{pl}$, where the plastic moment of resistance of the rectangular section $W_{pl}=bd^2/3.5$. When calculating the bending moments $M_{Edu}$, the force arms $F_{Edu}/8$ were taken as equal to 0.175 m and 0.29 m, taking into account the triangular pressure plot along the length of the platform for transferring these forces to the sample in accordance with the provisions of the deformation method.

Table 4

Destructive compressive forces and bending moments in concrete samples

| Sample designation | Destructive efforts | | | $M_{Rd}$ theory (at $f_{ctk,0.05}$) | $M_{exp}/M_{Rd}$ theory |
|---|---|---|---|---|---|
| | $M_{Edu}$, kNm | $F_{Edu}/8$, kN | $F_{Rdu}$, kN from (3) | | |
| 3-5 | 7.332 | 11.442 | 1172.1 | 6.296 | 1.163 |
| 3-6 | 3.661 | 5.721 | 764.4 | 3.875 | 0.945 |
| 3-8 | 3.488 | 5.45 | 764.4 | 3.875 | 0.900 |
| 3-17 | 8.374 | 13.084 | 866.3 | 6.800 | 1.231 |
| 3-24 | 11.505 | 17.976 | 866.3 | 6.800 | 1.692 |

Analysis of the comparison results confirms the nature of the destruction of concrete samples along normal cross-sections since the actual strength of inclined sections on the cut when pushing is an order of magnitude higher. Reducing the push angle from 40° to 34° led to an increase in bearing capacity by 13–14 %, taking into account coefficients of 0.8=160/200 when reducing to a base height of 160 mm and 0.81=0.17/0.21 while reducing concrete tensile strength to baseline strength.

The experimental destructive force for reinforced samples was also compared with the estimation shear resistance force when pushing the bases of slabs and columns without transverse reinforcement $V_{Rdc}$ according to current standards.

The shear resistance force during compression of the bases of slabs and columns without transverse reinforcement was determined by the dependence:

$$V_{Rdc} = C_{Rd,c}K\left(100\rho_1 f_{ck}\right)^{1/3}, \qquad (4)$$

where $K$=1+(200/$d$)$^{1/2}$≤2,0 is the coefficient of influence of the working height of the sample, taken as 2.0 for all samples;

$C_{Rd,c}$=0.035·($f_{ck}$)$^{1/3}$ – strength of concrete in cut (shear) according to [9];

$\rho_1=(\rho_{1y}\cdot\rho_{1z})^{1/2}\le 0.02$ – average percentage of reinforcement in the compression area;

$f_{ck}$ – the characteristic value of the compressive strength of concrete.

When determining $\rho_1$, only the reinforcing bars of the grids within the compression cone were taken into account.

Known dependences derived on the basis of hypotheses [10, 14, 15] were modified for the case of horizontal reinforcement of inclined cross-sections in the compression zone. It is recommended to determine the estimation load-bearing capacity during compression depending on:

$$F_{\max Rd} = F_\gamma \cos\gamma + F^h_{sw} + F_n \sin\gamma, \qquad (5)$$

where $F_v=2k_d f_{ctm}A\cdot\mathrm{ctg}\gamma$ is the tangential component of concrete strength in an inclined cross-section;

$F^h_{sw}$ – forces in the horizontal reinforcement taking into account the nagel effect according to (2);

$F_n=k_d f_{ctm}$A – normal component of concrete strength in an inclined cross-section;

$k_d$=1+0.07lgv is the dynamism factor;

$v$ – speed of load application.

The destruction effort was compared with the estimation ones for (4), (5), given in Table 5.

When calculating the static ($k_d$=1) component of $F_v$ and $F_n$ (Table 6), the estimation area A, according to (5), was assumed equal to 0.253 m$^2$ (samples 3-1...3-12) and 0.2918 m$^2$ (samples 3-13...3-24). In addition, the tensile strength of concrete $f_{ctm}$, obtained experimentally by testing cubes for splitting with rods with a diameter of 12 and 14 mm, was used.

These results correlate well with the actual nature of the destruction. Yes, samples 3-1...3-4, 3-7, 3-10 collapsed simultaneously when bending and forming pushing cracks and horizontal cracks splitting in the mesh plane while concrete samples and the reinforced samples 3-11, 3-12 collapsed when bending at the moment. Deviations of the estimation and experimental data downwards are associated with the deviation of horizontal grids from the design position. All concrete samples collapsed when bent along normal cracks as the actual compressive strength for them is twice as high. The same holds for samples 3-1, 3-9, 3-10, which collapsed during bending due to displacement of the grids from the design position, and for samples 3-11 and 3-12, which collapsed during bending. In these samples, at the stage of destruction, the first cracks from pushing were formed (deviations downwards in the range of 16–31 %). A comparison of the bearing capacity of the inclined cross-sections of reinforced concrete samples with the same reinforcement at different speeds of load application is given in Table 6. The comparison (samples 3-1, 3-3 and 3-18, samples 3-12 and 3-21, 3-23) shows that its increase was caused by an increase in the working height and a change in the angle of destruction.

Table 5

Comparison of the experimental strength of inclined cross-sections with the estimation one, taking into account the strength of concrete $V_{Rdc}$ and the nagel effect in reinforcement

| Sample designation | $F_{Edu}$, $kN$ | $f_{ck}$, MPa | $C_{Rdc}$, kN | $\rho_1$ | $4V_{Rdc}$, kN | $F^h_{sw}$, kN | $4V_{Rdc}+F^h_{sw}$, kN | $F_{Edu}/4V_{Rdc}+F^h_{sw}$ |
|---|---|---|---|---|---|---|---|---|
| 3-1 | 104.67 | 12.0 | 0.801 | 0.0065 | 12.71 | 16.30 | 29.01 | 3.61 |
| 3-2 | 222.29 | 20.0 | 0.95 | 0.0055 | 16.90 | 18.97 | 35.87 | 6.20 |
| 3-3 | 104.67 | 12.0 | 0.801 | 0.0065 | 12.71 | 16.30 | 29.01 | 3.61 |
| 3-4 | 346.59 | 20.0 | 0.95 | 0.0098 | 20.49 | 29.06 | 49.55 | 6.99 |
| 3-7 | 281.15 | 20.0 | 0.95 | 0.0098 | 20.49 | 29.06 | 49.55 | 5.67 |
| 3-9 | 71.91 | 12.0 | 0.801 | 0.0037 | 10.53 | 10.64 | 21.17 | 3.40 |
| 3-10 | 156.96 | 20.0 | 0.95 | 0.0065 | 17.87 | 23.72 | 41.59 | 3.77 |
| 3-11 | 71.91 | 20.0 | 0.95 | 0.0065 | 17.87 | 16.30 | 34.17 | 2.10 |
| 3-12 | 91.53 | 20.0 | 0.95 | 0.0055 | 16.90 | 13.03 | 29.93 | 3.06 |
| 3-13 | 294.3 | 15.0 | 0.863 | 0.0088 | 16.32 | 15.14 | 31.46 | 9.35 |
| 3-14 | 170.01 | 15.0 | 0.863 | 0.0088 | 16.32 | 15.14 | 31.46 | 5.40 |
| 3-15 | 130.77 | 12.0 | 0.801 | 0.0078 | 13.50 | 20.96 | 34.46 | 6.24 |
| 3-16 | 143.91 | 15.0 | 0.863 | 0.0029 | 11.27 | 12.41 | 23.68 | 6.08 |
| 3-18 | 130.77 | 12.0 | 0.801 | 0.0052 | 11.80 | 17.11 | 28.91 | 4.52 |
| 3-19 | 209.25 | 15.0 | 0.863 | 0.0059 | 14.28 | 15.14 | 29.42 | 7.11 |
| 3-20 | 235.44 | 15.0 | 0.863 | 0.0059 | 14.28 | 15.14 | 29.42 | 8.00 |
| 3-21 | 156.96 | 12.0 | 0.801 | 0.0088 | 14.06 | 13.67 | 27.73 | 5.66 |
| 3-22 | 150.39 | 12.0 | 0.801 | 0.0078 | 13.50 | 20.96 | 34.46 | 4.36 |
| 3-23 | 156.96 | 12.0 | 0.801 | 0.0044 | 11.16 | 13.67 | 24.83 | 6.32 |

Table 6

Comparison of experimental and calculated (for (5)) strength of inclined cross-sections

| Sample designation | $F_{\max Ed}$, kN | $F_v\cos\gamma$, kN | $F_n\sin\gamma$, kN | $F^h_{sw}$, kN | $F_{\max Rd}$, kN | $F_{\max Ed}/F_{\max Rd}$ | Nature of destruction |
|---|---|---|---|---|---|---|---|
| 3-1 | 104.67 | 65.72 | 27.65 | 16.30 | 109.67 | 0.954 | for $M$ and $F$ |
| 3-2 | 222.29 | 139.17 | 58.55 | 18.97 | 216.69 | 1.026 | for $M$ and $F$ |
| 3-3 | 104.67 | 65.72 | 27.65 | 16.30 | 109.67 | 0.954 | for $M$ and $F$ |
| 3-4 | 346.59 | 139.17 | 58.55 | 29.06 | 226.78 | 1.528 | for $M$, $F$ and $F^h_{crc}$ |
| 3-7 | 281.15 | 139.17 | 58.55 | 29.06 | 226.78 | 1.24 | for $M$, $F$ and $F^h_{crc}$ |
| 3-9 | 71.91 | 65.72 | 27.65 | 10.64 | 104.01 | 0.691 | for $M$ |
| 3-10 | 156.96 | 139.17 | 58.55 | 23.72 | 221.44 | 0.709 | for $M$ and $F$ |
| 3-11 | 71.91 | 65.72 | 27.65 | 16.30 | 109.67 | 0.656 | for $M$ |
| 3-12 | 91.53 | 65.72 | 27.65 | 13.03 | 106.40 | 0.86 | for $M$ |
| 3-13 | 294.3 | 101.6 | 34.26 | 15.14 | 151.0 | 1.949 | for $M$, $F$ and $F^h_{crc}$ |
| 3-14 | 170.01 | 101.6 | 34.26 | 15.14 | 151.0 | 1.126 | for $M$ and $F$ |
| 3-15 | 130.77 | 82.25 | 27.73 | 20.96 | 130.94 | 0.999 | for $M$ and $F$ |
| 3-16 | 143.91 | 101.6 | 34.26 | 12.41 | 148.27 | 0.971 | for $M$ and $F$ |
| 3-18 | 130.77 | 82.25 | 27.73 | 17.11 | 127.09 | 1.029 | for $M$ and $F$ |
| 3-19 | 209.25 | 101.6 | 34.26 | 15.14 | 151.0 | 1.386 | for $M$ and $F$ |
| 3-20 | 235.44 | 101.6 | 34.26 | 15.14 | 151.0 | 1.559 | for $M$ and $F$ |
| 3-21 | 156.96 | 82.25 | 27.73 | 13.67 | 123.65 | 1.264 | for $M$, $F$ and $F^h_{crc}$ |
| 3-22 | 150.39 | 82.25 | 27.73 | 20.96 | 130.94 | 1.149 | for $M$ and $F$ |
| 3-23 | 156.96 | 82.25 | 27.73 | 13.67 | 123.65 | 1.264 | for $M$ and $F$ |

With a different class of concrete (samples 3-4, 3-7 and samples 3-15, 3-22), the increase in the tensile strength of concrete by 1.5 times fully compensates for the decrease in the working height and increases the bearing capacity by 2.25 times. Increasing the thickness of the protective structure is not an effective method for increasing the bearing capacity of inclined cross-sections for compression as it does not compensate for the decrease in the area of destruction (truncated cone) with an increase in the speed of load application. It is more effective to arrange an additional row of reinforcement – a mesh near the face on which the compressive force acts. This gives an increase in strength from 55 % (comparing sample 3-16 with 3-19, 3-20) to 65 % (comparing sample 3-13 with 3-21, 3-23, reduced to concrete with $f_{cd}$=7.5 MPa).

When developing design proposals, it is taken into account that the highest values of cracking forces were obtained when using layer-by-layer horizontal reinforcement. The desired effect is achieved by the reinforcement of the stretched zone, the faces of applying the external load and additional horizontal reinforcement in the middle of the cross-sectional height of the protective structure. Restrictions on the maximum diameters of reinforcement (12–14 mm), its pitch (50–125 mm), minimum class of concrete (C16/20) make it possible to completely avoid the appearance of the most dangerous cracks in splitting. The proposed structural measures make it possible to significantly reduce the level of damage under the action of an emergency dynamic compression load and to reduce the costs of repair and restoration of operational suitability.

## 6. Discussion of results of studying the inclined cross-sections on the effect of emergency local pushing

In general, the test results show that by the time of destruction, the entire height of the concrete section and fair hypotheses work for pushing [3, 4]. Although in the current norms of DSTU B V.2.6-156-2010 at static (pushing angle more than 63.4°) and emergency dynamic loads with pushing angles within 45–63.4° [18], only working cross-sectional height $d$ is included in the calculation. The comparison of the results given in Table 4 shows that the strength of the samples with the same reinforcement is significantly influenced by the class of concrete. The strength of inclined cross-sections is twice as low in samples of C10/12 class concrete as compared to C16/20 class concrete. In addition, in the C16/20 concrete samples, no cracking from splitting in the plane of the grids was recorded, which allows us to recommend this class of concrete as the minimum for protective structures under compression.

The results of experimental studies (Tables 3, 4) of inclined cross-sections confirmed the possibility of determining the bearing capacity of reinforced concrete shells of protective structures with horizontal reinforcement under the action of an emergency local pushing load according to modified dependences of the hypothesis [10, 14, 15]. When replacing the integral coefficient of reinforcement in the calculation $F_n$ with the additional force from the nagel effect of the reinforcement in the calculation $F_v$, the error does not exceed 13.8–20.7 %. At the same time, it is recommended to use the value of $f_{ctm}$ obtained experimentally when splitting with rods, the diameter of which corresponds to the diameter of the working armature of horizontal grids. Deviations of experimental data from the calculated ones are associated with deviations noted by many other researchers of the actual tensile strength of concrete, which is less stable compared to compressive strength. The dependence of norms (3) does not take into account the change in the angle of destruction, which led to significant differences with experimental studies. In general, the dependences of the current norms for calculating the shear strength of concrete cross-sections and for partially loaded zones yield deviations many times from those obtained experimentally. This excludes their use in calculations for crushing by local emergency dynamic loads.

The obtained results (Table 4) of the comparison of the values of strength and crack resistance of reinforced inclined and horizontal cross-sections allow us to provide practical recommendations for their design. Design features concern areas of local compression of reinforced concrete slabs and shells of protective structures by an emergency dynamic load, the speed of which corresponds to the failure angles of 34–45°. Increasing the crack resistance of the cross-sections is achieved by combining the reinforcement of the stretched and compressed zones of the bent section with additional reinforcement in the middle of the height at the most effective level from the point of view of providing against crushing.

The results of the our research concern dynamic loads that cause destruction at angles of 45–34°. A disadvantage of the study can be considered the fact that samples from fiber concrete were not examined, which would allow additional study of the effect of fiber on the crack resistance of sections under emergency dynamic effects. For the fracture angles of 25–34°, it is necessary to investigate the possible features of crack formation and fracture with three rows of horizontal grids. It is also necessary to more deeply investigate the influence of the clamp effect on the crack resistance of inclined cross-sections in the compression zone. For fracture angles less than 34°, additional experimental studies are recommended. This will allow more accurate calculation of protective structures for emergency loads with higher application speeds. The continuation of research to ensure reliable calculations of the strength of shelters when designing them and verification calculations of existing building ceilings when adapting them for shelters is especially relevant. For such sections in horizontal grids, it is structurally recommended to use reinforcement with a diameter of 12, 14 mm with a step of 50–125 mm. When designing, it is recommended to use double reinforcement with an additional mesh near the outer edge, on which the effect of emergency compression is possible. It is recommended to take the class of concrete not lower than C16/20 and to additionally maximize the tensile strength of concrete (use of polypropylene, steel fiber, etc.).

In the future, it is necessary to investigate the effect of the preliminary stress of the reinforcement on the clipping effect in the pushing zone, which also affects the increase in crack resistance of this zone.

## 7. Conclusions

1. Experimental studies of samples – fragments of a monolithic shell (slab) of a protective structure with

horizontal reinforcement at different levels in terms of cross-sectional height at two angles of destruction were carried out. The results made it possible to establish the influence of angles of 34–45° (the rate of application of the local emergency pushing load) and their changes on the crack resistance and strength of normal, inclined, and horizontal cross-sections. Under dynamic loads that cause failure at an angle of 34°, the compressive strength of unreinforced sections increases by 13–14 % compared to failure at an angle of 40°. The installation of an additional mesh near the face on which the compressive force acts increases the strength by 55–65 %.

2. Under the action of an emergency dynamic pushing load, the bearing capacity of a protective structure with horizontal reinforcement can be determined by the design scheme of the cut cone according to hypotheses [10, 14, 15]. The integral reinforcement coefficient when calculating $F_n$ is replaced by additional force from the layer effect of the reinforcement. When calculating $F_v$, it is necessary to use the value of $f_{ctm}$, obtained experimentally by splitting with rods, the diameter of which corresponds to the diameter of the working reinforcement of horizontal grids. The discrepancy between the results of experimental studies and the calculation does not exceed 20.7 %. The use of dependences from current standards cannot be applied in the calculations of crack resistance and on the cut of inclined sections when pushing by local emergency dynamic load since they do not take into account the characteristics of this load. The deviation of the calculated values from those obtained experimentally at the same time exceeds 100 %. Structurally, to increase crack resistance in the pushing zone, it is recommended to limit the maximum diameters of the mesh reinforcement to values of 12–14 mm, the pitch of the rods with values of 50–125 mm, and the concrete class to be taken not lower than C16/20.

## Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

## References


1. Bindi, D., Massa, M., Luzi, L., Ameri, G., Pacor, F., Puglia, R., Augliera, P. (2013). Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5 %-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. Bulletin of Earthquake Engineering, 12 (1), 391–430. doi: https://doi.org/10.1007/s10518-013-9525-5
2. Boore, D. M., Stewart, J. P., Seyhan, E., Atkinson, G. M. (2014). NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. Earthquake Spectra, 30 (3), 1057–1085. doi: https://doi.org/10.1193/070113eqs184m
3. Bozorgnia, Y., Campbell, K. W. (2016). Vertical Ground Motion Model for PGA, PGV, and Linear Response Spectra Using the NGA-West2 Database. Earthquake Spectra, 32 (2), 979–1004. doi: https://doi.org/10.1193/072814eqs121m
4. Çağnan, Z., Akkar, S., Kale, Ö., Sandıkkaya, A. (2016). A model for predicting vertical component peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudospectral acceleration (PSA) for Europe and the Middle East. Bulletin of Earthquake Engineering, 15 (7), 2617–2643. doi: https://doi.org/10.1007/s10518-016-0063-9
5. Du, W., Wang, G. (2012). A simple ground-motion prediction model for cumulative absolute velocity and model validation. Earthquake Engineering & Structural Dynamics, 42 (8), 1189–1202. doi: https://doi.org/10.1002/eqe.2266
6. Foulser-Piggott, R., Goda, K. (2015). Ground-Motion Prediction Models for Arias Intensity and Cumulative Absolute Velocity for Japanese Earthquakes Considering Single-Station Sigma and Within-Event Spatial Correlation. Bulletin of the Seismological Society of America, 105 (4), 1903–1918. doi: https://doi.org/10.1785/0120140316
7. Sedaghati, F., Pezeshk, S. (2017). Partially Nonergodic Empirical Ground-Motion Models for Predicting Horizontal and Vertical PGV, PGA, and 5% Damped Linear Acceleration Response Spectra Using Data from the Iranian Plateau. Bulletin of the Seismological Society of America, 107 (2), 934–948. doi: https://doi.org/10.1785/0120160205
8. Maksymovych, S., Krochak, O., Karkhut, I., Vashkevych, R. (2020). Experimental Study of Crack Resistance and Shear Strength of Single-Span Reinforced Concrete Beams Under a Concentrated Load at a/d = 1. Proceedings of EcoComfort 2020, 277–285. doi: https://doi.org/10.1007/978-3-030-57340-9_34
9. Blikharskyi, Z. Ya., Karkhut, I. I. (2017). Rozrakhunok i konstruiuvannia zghynanykh zalizobetonnykh elementiv. Lviv: Vydavn. Lvivskoi politekhniky, 186.
10. Korenev, B. G., Smirnova, A. F. (Eds.) (1986). Dinamicheskiy raschet spetsial'nykh inzhenernykh sooruzheniy i konstruktsiy. Spravochnik proektirovschika. Moscow: Stroyizdat, 461.
11. Duan, Z., Zhang, L., Wen, L., Guo, C., Bai, Z., Ou, Z., Huang, F. (2018). Experimental research on impact loading characteristics by full-scale airplane impacting on concrete target. Nuclear Engineering and Design, 328, 292–300. doi: https://doi.org/10.1016/j.nucengdes.2018.01.021
12. Králik, J. (2014). Safety of Nuclear Power Plants against the Aircraft Attack. Applied Mechanics and Materials, 617, 76–80. doi: https://doi.org/10.4028/www.scientific.net/amm.617.76
13. Eibl, J. (2003). Airplane Impact on Nuclear Power plants. Proceedings of the 17th international conference on structural mechanics in reactor technology. Prague. Available at: https://inis.iaea.org/search/search.aspx?orig_q=RN:36071655

14. Kirillov, A. P., Sargsyan, A. E. (1982). Raschet zaschitnoy obolochki na vozdeystvie padayuschego samoleta. Materialy konferentsiy i soveschaniy po gidrotekhnike: Predel'nye sostoyaniya betonnykh i zhelezobetonnykh konstruktsiy energeticheskikh sooruzheniy. Leningrad: Energoizdat, 151–159.
15. Makarenko, L. P. (1986). Rekomendatsii po raschetu zhelezobetonnykh zaschitnykh obolochek AES v avariynoy situatsii. Rovno, 22.
16. Blikharskyy, Z., Khmil, R., Vegera, P. (2017). Shear strength of reinforced concrete beams strengthened by P.B.O. fiber mesh under loading. MATEC Web of Conferences, 116, 02006. doi: https://doi.org/10.1051/matecconf/201711602006
17. Blikharskyy, Z., Vegera, P., Vashkevych, R., Shnal, T. (2018). Fracture toughness of RC beams on the shear, strengthening by FRCM system. MATEC Web of Conferences, 183, 02009. doi: https://doi.org/10.1051/matecconf/201818302009
18. Karkhut, I. I. (2021). Design and Construction in Areas with High Seismic Activity. Lviv, 188. Available at: https://vlp.com.ua/node/20395
19. Bychenkov, Yu. D., Bespaev, A. A. (1971). Prochnost' i treschinostoykost' uzlov ram zhelezobetonnogo karkasa seysmostoykikh mnogoetazhnykh zdaniy. Beton i zhelezobeton, 2.
20. Babaev, V. N., Bambura, A. N., Pustovoitova, O. M., Reznyk, P. A., Stoianov, Ye. H., Shmukler, V. S. (2015) Praktychnyi rozrakhunok elementiv zalizobetonnykh konstruktsiy za DBN V.2.6-98:20009 u porivnianni z rozrakhunkamy za SNyP 2.03.01-84* i EN 1992-1-1 (Eurocode 2). Kharkiv: Zolotye stranitsy. Available at: http://eprints.kname.edu.ua/42750/