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Analytical, experimental and numerical results of determination of natural frequencies and forms of oscillations of reinforced concrete and fiber-reinforced concrete hollow core slabs are given. The problem of determination of natural frequencies and forms of oscillations of reinforced concrete and fiber-reinforced concrete slabs at the initial modulus of elasticity is solved analytically. Computer modeling of the considered constructions in two software complexes is performed and the technique of their modal analysis on the basis of the finite element method is developed. Experimental researches of free oscillations of the considered structures are carried out and the comparative analysis of all received results is carried out. The frequency spectrum calculated by the finite element method (ANSYS) is approximately 4% lower than calculated analytically; the results of the calculation in SOFiSTiK differ by 2% from the results obtained in ANSYS; the discrepancy with the experimental data reaches 15%, and all frequencies calculated experimentally, greater than the frequencies calculated analytically or by the finite element method. The obtained frequency range of fiber concrete slabs is higher than that of concrete, which gives reason to recommend fiber reinforced concrete for the manufacture of structures that will work under dynamic influences.

Keywords: slab, concrete, fiber-reinforced concrete, dynamic, modal analysis, oscillation frequency, form of oscillation, model, finite elements method, SOFiSTiK, ANSYS.

Author: odesa state academy of civil engineering and architecture.

I. INTRODUCTION

The work of reinforced concrete structures, including slabs, under static loads has been studied quite well. And the issues of plate dynamics are much less well covered. At the same time, the emphasis in research is placed on short-term loads–impulse, impact, explosion. Meanwhile, when solving almost any problem of dynamics, it becomes necessary to determine the natural frequencies and modes of vibration, since these parameters determine the behavior of the system under other types of dynamic influences.

Dynamic calculations of reinforced concrete structures are associated with solving a set of issues: determining the parameters of dynamic loads, limiting states, taking into account changes in the strength and deformation characteristics of concrete and reinforcement, determining forces and deformations in structures, etc.

The nature of reinforcement makes a significant contribution to the nature of changes in the dynamic parameters of reinforced concrete structures. This fact is well known, but has not yet been thoroughly studied, either quantitatively or qualitatively. And the influence of dispersed reinforcement, in particular, steel fiber, on the dynamic parameters has been studied even less.

Despite the growing interest in steel fiber concrete and the corresponding increase in publications, the available data are contradictory, have a certain incompleteness, which allows us to give only a general assessment of the results presented in them. So, research in this direction is relevant.

II. ANALYSIS OF PUBLICATIONS

The behavior of reinforced concrete slabs under static loads is reflected in the works [1-5]. Slabs with dispersed reinforcement are described in [6-9]. Let us dwell on these works in more detail. So, in [6], the effect of steel fiber added to reinforced concrete slabs is studied. Four-point bending tests are carried out on six slabs to investigate the structural behavior of the slabs taking into account two different parameters – slab thickness and steel fiber volume fraction. In [7], the possibility of limiting the crack width in concrete industrial floors is studied by adding steel fiber to the mixture. In [8], a comparison of the properties of concrete slabs with two types of added fibers is presented. One sample had no fibers and served as a control. The other four had steel and polypropylene fibers added in different volumetric ratios. Interesting is the work [9], where several full-size road slabs reinforced with different volume fractions of steel fibers with different geometries at a point load in the center of the slab are studied.

The issues of plate dynamics are studied in [10-15]. Seven slabs were tested under drop load in [10]. The test results showed that the addition of steel fibers was very effective. In [11], the process of deformation and destruction of a reinforced concrete slab under the influence of an air shock wave is considered. The plate is loaded by detonating an explosive in a shock tube. Numerical modeling is carried out in the LS-DYNA package, the finite element method with an explicit time integration scheme is used.

Analysis of publications shows that the problem of determining the natural frequencies and modes of vibrations of plates is still poorly understood.

III. PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of this work is analytical, experimental and numerical determination of natural frequencies and forms of oscillations of reinforced concrete and fiber-reinforced concrete hollow core slabs.

IV. PROBLEM FORMULATION

To achieve this goal, it is necessary to solve the following tasks:

1. Analyze modern analytical, numerical and experimental methods for studying the dynamics of reinforced concrete and fiberreinforced concrete slabs.
2. Solve analytically the problem of determining the natural frequencies and modes of vibration of reinforced concrete and fiberreinforced concrete slabs.
3. Perform computer modeling of the structures under consideration and develop a method for their modal analysis based on the finite element method.
4. Carry out experimental studies of free vibrations of the structures under consideration and a comparative analysis of all the results obtained.

V. RESEARCH RESULTS

A series of models of hollow core floor slabs (Fig. 1) with reinforcing rod reinforcement class A III was made. The geometric dimensions of the model are reduced by half in relation to the dimensions of the serial slab. In this case, for technological reasons (fiber size), model plates have 5 voids, not 6, as in serial plates. At the preliminary stage of research from concrete and fiber concrete of the same mixes cubic samples of 100 × 100 × 100 mm were made and tested on compression up to destruction that allowed to establish a class of concrete (C16/20) according to norms (big filler of fraction less than 10 mm).

During the tests, different physical and mechanical characteristics of the two materials were determined, including those required for dynamic calculations. These values were used in analytical calculations and in numerical simulations.

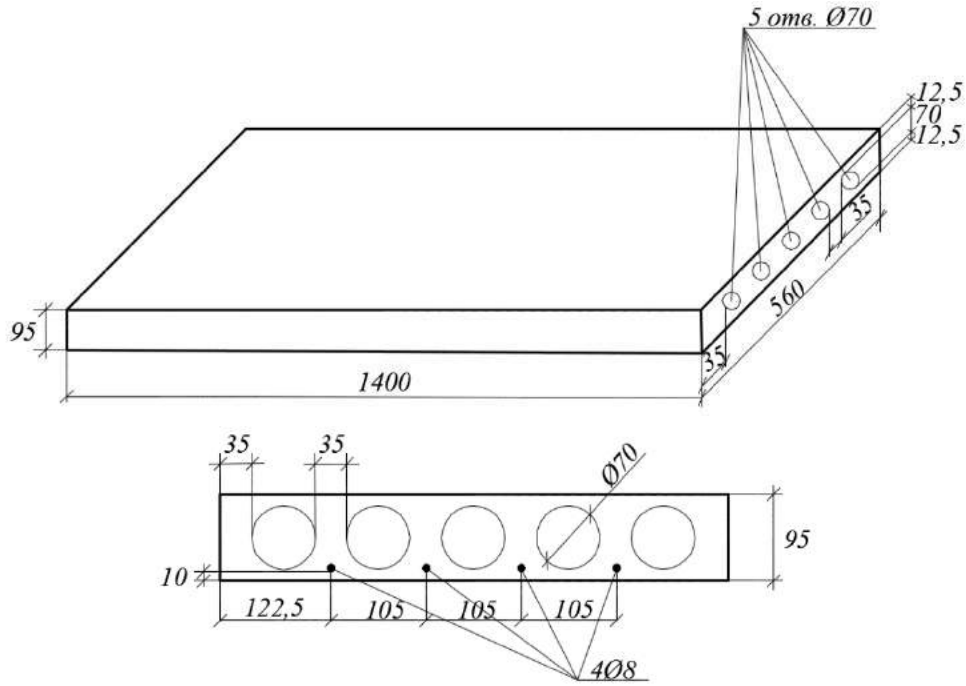

Fig. 1: Model of reinforced concrete hollow core slab

Static tests of model slabs made of reinforced concrete were carried out on a specially mounted test bench. The scheme of loading is shown in Fig. 2. In the course of these tests, the load was applied in steps of 10% of the calculated value of the destructive load.

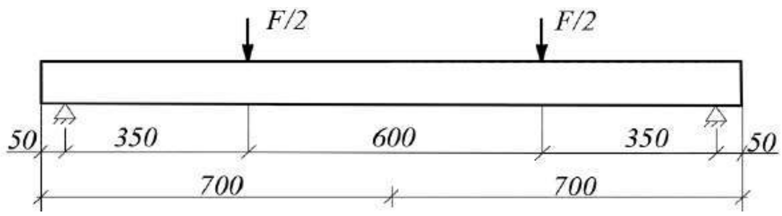

Fig. 2: Load scheme

In classical dynamics it is shown that the form of the differential equation of free oscillations under the action of a system of constant forces will be the same as in their absence, if the displacement of the body is subtracted from the position of its static equilibrium [16]. This means that in the field of elastic deformations, the natural frequency does not depend on the external static load on the structure. As a result of static tests, it was found that the process of crack formation in the plates begins at the seventh stage of loading, at a load of 16.6 kN. The fracture moment of 2.94 kNm, the same for all tested plates, was recorded here. The destructive load was 27.9 kN at the seventh stage of loading at 15.41 kNm.

Thus, the load at the beginning of the crack is approximately 0.6 of the actual value of the destructive load. Therefore, when determining the frequencies and forms of free oscillations of the reinforced concrete slab, we can assume that the deformation is elastic not only in the absence of external static load, but also when it changes in the range from 0 to 0.5 of the actual destructive load.

In the course of our work we performed analytical, computer and experimental studies of model hollow slabs (concrete and fiber-reinforced concrete) under two variants of boundary conditions - hinged support along the entire contour and hinged support on two short sides and free two other sides, as well as serial hollow slabs (concrete and fiber concrete) with hinged support on two short sides and free two other sides.

The next experiment was performed with serial multi-hollow floor slabs by conductin g full-scale static and dynamic tests in the laboratory(Fig. 3).

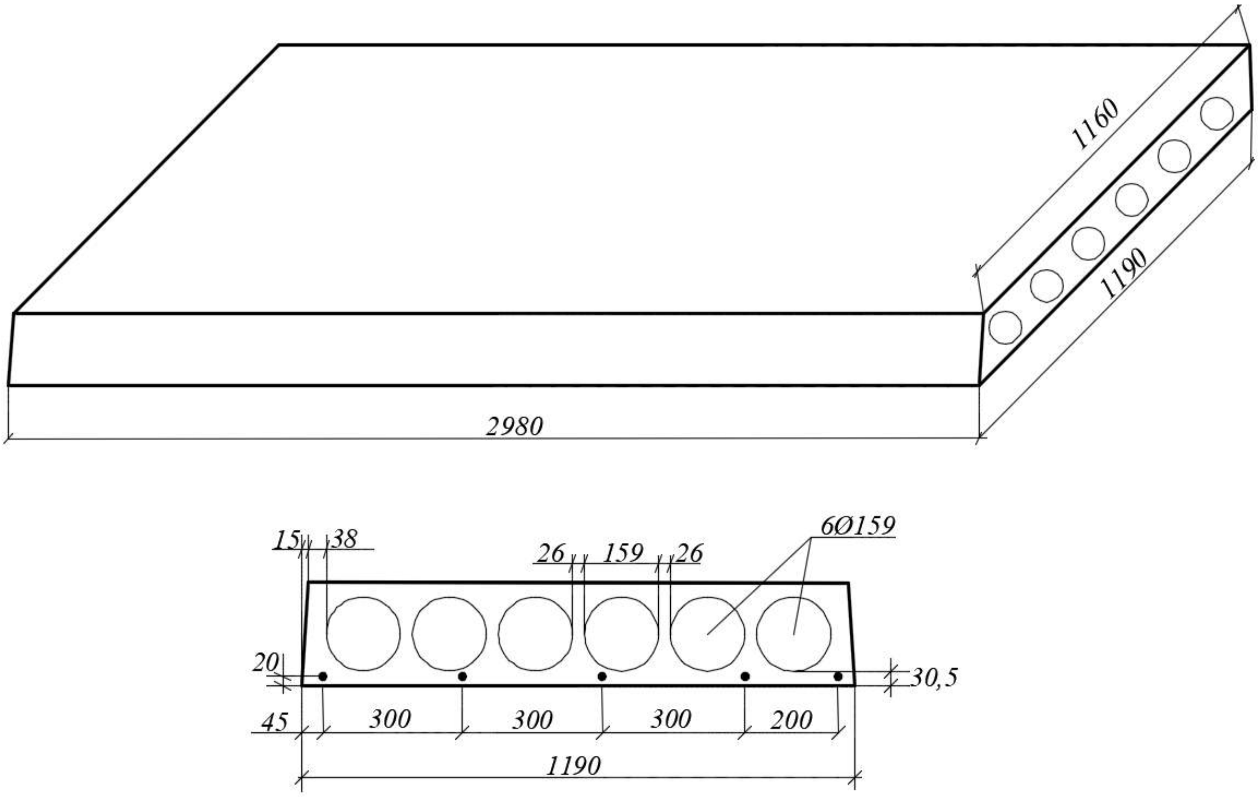

Fig. 3: Serial hollow core floor slab

Floor slabs are manufactured at the reinforced concrete plant in accordance with regulatory documents. For the manufacture of slabs used concrete C16/20 and reinforcement AIVC. Moreover, in the manufacture of one of the plates in the concrete mixture was added 1% steel anchor fiber.

The study of the strength properties of concrete was performed in the factory on samples-cubes with a rib size of 10 cm, which are tested for compression, and obtained the cubic strength corresponding to concrete C16/20. Determination of the strength of concrete under short-term loading was performed in accordance with the requirements of current regulations.

Analytically, the natural frequencies are determined by known formulas [17].

Experimental dynamic tests of the slab were carried out in the laboratory of the Department of Structural Mechanics of the Odessa State Academy of Civil Engineering and Architecture on a specially made test banch [18].

At dynamic tests for disturbance of cross oscillations the shock method possessing a number of advantages was used: simplicity of realization of the damped blow by means of the special shock device; no need to determine the logarithmic decrement of oscillations, the probability of which depends on the accuracy of the conditions of equality of the oscillatory energy supplied to the controlled structures. The impact uses an electromagnetic shock device, which is a modified to the required operating conditions contactor with a capacitive drive, the power of which can reach 600 J.

To create a damping shock, the surface of the rod in contact with the lower face of the test structure is covered with a layer of technical rubber, which reduces the duration of the transition period of the oscillating process.

The first four natural frequencies of oscillations of concrete and fibroconcrete model hollow slabs were experimentally determined in two variants of support - hinged along the entire contour (Table 1) and hinged support on two short sides with free two other sides (Table 2).

At the next stage, the first four natural frequencies of oscillations of concrete and fiber-reinforced concrete serial slabs with hinged support on two short sides with free two other sides were experimentally determined (Table 3). The natural frequencies determined experimentally are significantly higher than the theoretical ones.

Similar results were obtained by some other authors. Attempts to explain the observed difference by the fact that the analytical formulas for the frequencies of transverse oscillations take into account the moment of inertia of the rod, which in the case of rod reinforcement or dispersed reinforcement must be calculated by special methods, fail.

Table 1: Experimental and analytical values of oscillation frequencies of concrete and fiber-reinforced concrete model slabs with hinged support along the contour

Material	Frequency, s^{-1}	Experiment	Calculation	Discrepancy, %
Concrete	ω_{11}	2620,2	2347,4	10,4
	ω_{21}	3802,8	3318,8	12,7
	ω_{12}	9720,2	8418,3	13,4
	ω_{22}	10917,4	9389,6	14,0
Fiber-reinforced concrete, 1,0 %	ω_{11}	2662,6	2383,0	10,5
	ω_{21}	3854,9	3369,2	12,6
	ω_{12}	9891,3	8546,1	13,6
	ω_{22}	11109,7	9532,1	14,2

Table 2: Experimental and analytical values of oscillation frequencies of concrete and fiber-reinforced concrete model slabs with hinged support on two short sides with two free sides

Material	Frequency, s^{-1}	Experiment	Calculation	Discrepancy, %
Concrete	ω_{11}	496,6	442,5	10,9
	ω_{21}	1722,2	1498,3	13,0
	ω_{12}	2051,9	1764,6	14,0
	ω_{22}	3905,0	3323,2	14,9
Fiber-reinforced concrete, 1,0 %	ω_{11}	528,3	469,7	11,1
	ω_{21}	1824,7	1582,0	13,3
	ω_{12}	2166,7	1867,7	13,8
	ω_{22}	4111,8	3490,9	15,1

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The algorithm for calculating the geometric characteristics of the so-called induced cross section is well known and is given in the numerous literature on reinforced concrete structures, however, based on the formulas of this algorithm, the effect of moment of inertia on oscillations will not be as significant as observed in the experiment. A more important explanation, in our opinion, is the incorrectness of the used dynamic model of reinforced plate. The classical dynamics of structures is known to be based on the theory of linear differential equations, and the oscillations of structures are considered in relation to the unstressed initial state.

Table 3: Experimental and analytical values of oscillation frequencies of concrete and fiber-reinforced concrete serial slabs with hinged support on two short sides with two free sides

Material	Frequency, s^{-1}	Experiment	Calculation	Discrepancy, %
Concrete	ω_{11}	245,8	222,2	9,6
	ω_{21}	844,0	742,7	12,0
	ω_{12}	1005,7	881,0	12,4
	ω_{22}	1891,9	1636,5	13,5
Fiber-reinforced concrete, 1,0 %	ω_{11}	262,4	235,9	10,1
	ω_{21}	892,0	788,5	11,6
	ω_{12}	1060,5	935,4	11,8
	ω_{22}	1997,2	1737,6	13,0

It is obvious that in the study of free and forced oscillations of reinforced concrete building structures such an approach is unsuitable because they are physically nonlinear systems. There are very few publications on the physically nonlinear dynamics of reinforced concrete structures, and the main attention is paid to methods for solving nonlinear equations of motion, and the concept of determining nonlinear terms of these equations is practically not studied. This requires experimental research and computer simulations to identify all the factors that affect the frequency spectrum.

Computer modeling and finite element modal analysis of hollow core slabs were performed in two packages – ANSYS [19] and SOFiSTiK [20]. In the tables 4–6 for the purpose of comparison the results of finite-element, experimental and analytical determination of frequencies in model and serial hollow slabs are summarized.

Table 4: Comparison of analytical, numerical and experimental values of frequencies of natural oscillations of model plates with hinged support on a contour

Slab	Frequency	ANSYS	SOFiSTiK	Experiment	Calculation
Reinforced concrete	1	2317,6	2311,6	2620,2	2347,4
	2	3300,8	3289,4	3802,8	3318,8
	3	8377,6	8357,8	9720,2	8418,3
	4	9309,0	9219,1	10917,4	9389,6
	5	12749,6	12359,8	Not determined	
Fiber-reinforced concrete	1	2353,0	2341,1	2662,6	2383,0
	2	3349,2	3329,7	3854,9	3369,2
	3	8506,3	8486,6	9891,3	8546,1
	4	9482,7	9372,1	11109,7	9532,1
	5	12819,2	12404,1	Not determined	

Table 5: Comparison of natural frequencies of model plates with hinged support on two sides

Slab	Frequency	ANSYS	SOFiSTiK	Experiment	Calculation
Reinforced concrete	1	427,5	423,1	496,6	442,5
	2	1441,2	1430,7	1722,2	1498,3
	3	1714,1	1675,9	2051,9	1764,6
	4	3233,9	3145,4	3905,0	3323,2
	5	6749,6	6459,8	Not determined	
Fiber-reinforce d concrete	1	451,7	446,7	528,3	469,7
	2	1531,6	1520,3	1824,7	1582,0
	3	1817,1	1769,1	2166,7	1867,7
	4	3398,6	3307,4	4111,8	3490,9
	5	6819,2	6504,1	Not determined	

Table 6: Comparison of natural frequencies of serial plates with hinged support on two sides

Slab	Frequency	ANSYS	SOFiSTiK	Experiment	Calculation
Reinforced concrete	1	218,6	216,6	245,8	222,2
	2	732,2	726,4	844,0	742,7
	3	868,4	860,1	1005,7	881,0
	4	1596,3	1579,1	1891,9	1636,5
	5	3749,6	3689,1	Not determined	
Fiber-reinforced concrete	1	231,1	229,1	262,4	235,9
	2	777,7	779,7	892,0	788,5
	3	921,1	912,6	1060,5	935,4
	4	1697,2	1662,1	1997,2	1737,6
	5	3789,2	3724,4	Not determined	

The above results of calculations were obtained at the initial modulus of elasticity, i.e. correspond to the state of the plates without external load.

VI. CONCLUSIONS

Despite the fact that both software packages (SOFiSTiK and ANSYS) implement the finite element method, the process of solving the problem in each of them has its own characteristics, which slightly, but still affect the result. The main ones are: first, different finite elements are involved in different programs; secondly, the processes of construction of a finite-element mesh differ and, as a consequence, the number of finite elements with the same geometric model of the structure.

A comparative analysis of all obtained theoretical, experimental and computer results showed the following:

- The frequency spectrum calculated by the finite element method (ANSYS) is approximately 4% lower than calculated analytically;
- The results of the calculation in SOFiSTiK differ by 2% from the results obtained in ANSYS;
- The discrepancy with the experimental data reaches 15%, and all frequencies calculated experimentally, greater than the frequencies calculated analytically or by the finite element method.

The obtained frequency range of fiber-reinforced concrete slabs is higher than that of concrete, which gives reason to recommend fiber-reinforced concrete for the manufacture of structures that will work under dynamic influences.

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