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NUMERICAL MODELING OF CAST-IN-PLACE REINFORCED CONCRETE BUBBLE DECK FLOOR SLABS UTILIZED IN EARTHQUAKE-PRONE REGIONS

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Abstract: This article presents developed techniques for numerical modelling of lightweight cast-in-place reinforced concrete bubbledeck floor slabs and a comparative analysis of different approaches to numerical modelling of buildings and structures with such lightweight floors, that are constructed in earthquake-prone regions.

Keywords: finite element method, modal analysis, earthquake excitation, mechanical safety, void formers, lightweight cast-in-place reinforced concrete floor slabs

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ МОНОЛИТНЫХ ЖЕЛЕЗОБЕТОННЫХ ПЕРЕКРЫТИЙ С ПУСТОТООБРАЗОВАТЕЛЯМИ, ПРИМЕНЯЕМЫХ В СЕЙСМИЧЕСКИ АКТИВНЫХ РАЙОНАХ

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Аннотация: В настоящей статье представлены разработанные авторами методики численного моделирования облегченных монолитных железобетонных перекрытий с пустотообразователями и сравнительный анализ различных подходов численного моделирования для зданий и сооружений, строящихся в сейсмически активных районах и имеющих в своём составе подобные облегчённые плиты перекрытий.

Ключевые слова: метод конечных элементов, модальный анализ, сейсмическое воздействие, механическая безопасность, пустотообразователи, облегченные монолитные железобетонные перекрытия

1. INTRODUCTION

Nowadays, a significant part of building constructions is made of cast-in-place reinforced concrete. Concrete high density and, hence, large dead weight of structural components made of it is a significant disadvantage. It leads to higher loads, in particular seismic ones, on vertical structural elements and foundations, increased construction costs and time. Therefore, different ways to decrease dead weight are employed when designing buildings and structures, particularly in earthquake-prone regions.

Utilization of void formers (see Fig. 1) is one of the ways to decrease the dead weight of concrete structures. The void formers to use in reinforced concrete floor slabs may be extractable and unextractable, may be made of different materials and have various shapes, as it is stated in [1]. For some types of void formers, there are proprietary standards [12] [13] and recommendations for calculation of a stress-strain state of voided floor slabs exposed to special combinations of loads [14].

There exists a large amount of researches on a bubbledeck floor slabs response to various excitations (see [2-11]). According to these studies, usage of bubbledeck floor slabs has a small impact onto structural strength, but at the same time reduces structural stiffness, that, evidently, affects an eigenfrequency spectrum of the considered building or structure.

When designing a building or a structure constructed in an earthquake-prone region, a response spectrum analysis is commonly performed with a large number of eigenmodes taken into account. Hence, utilization of a bubbledeck floor slab solution should be explicitly taken into account during the design procedure, in particular when calculating the design stress-strain state.

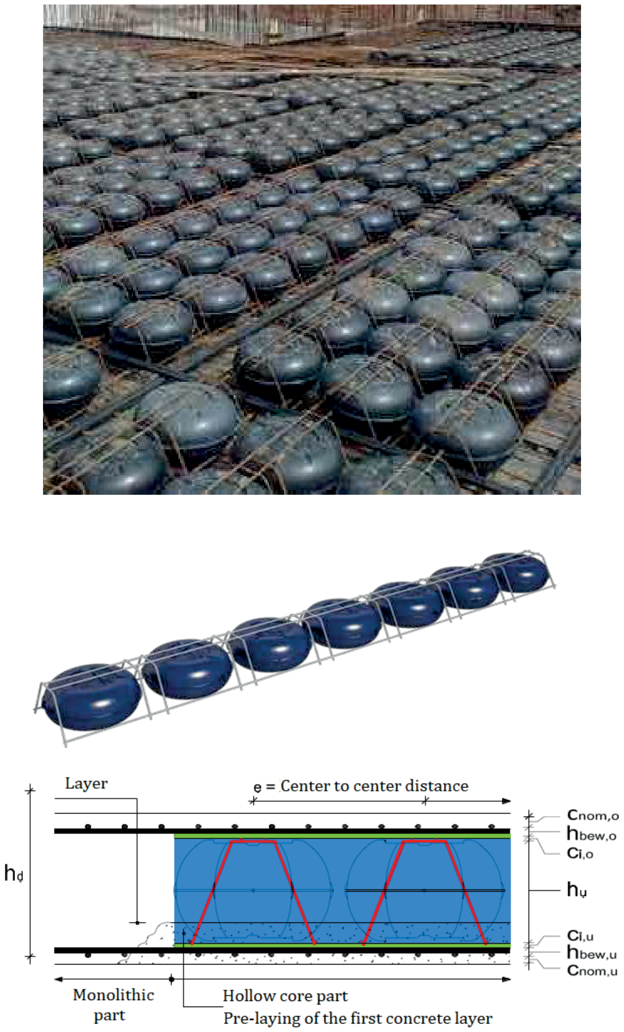


Figure 1. An example of void formers used in reinforced concrete floor slabs, and their geometrical parameters

The finite element method (FEM) is widely used to perform such an analysis. The most accurate way to compute eigenfrequencies, eigenmodes and a stress-strain state of structural elements with a complex shape of the cross-section (for instance, a hollow core structure) is to use solid finite elements for spatial discretization of the problem. Yet, such a technique is computationally ineffective and, thus, used in practice very rarely. A common practice is to use structural finite elements, shell and beam ones, to spatially discretize a structural mechanics problem.

In the present paper considered are different approaches to numerical modelling of lightweight cast-in-place reinforced concrete bubbledeck floor slabs with an aim to correctly simulate floor slab stress-strain state, elastic stiffness and eigenfrequency spectrum, that allows one to utilize such an approach in design practice.

2. PROBLEM FORMULATION

To evaluate an accuracy of different approaches to numerical modelling of lightweight cast-in-place reinforced concrete bubbledeck floor slabs, a single floor cell of a reinforced concrete frame building has been considered (see Fig. 2).

The chosen part of the floor slab has dimensions of 5.6×5.6 meters and comprises 16 void former cells in each direction. The floor slab has the following values of its geometrical parameters: the floor slab thickness h_d = 250mm; the void former height h_u = 140mm; the concrete cover at the upper slab face $c_{nom,o}$ = 20mm; the concrete cover at the lower slab face $c_{nom,u}$ = 20mm; the distance between bubbles centers e = 350mm; the void former diameter d = 315mm. A cross-section of the single void former cell is shown in Fig. 3.

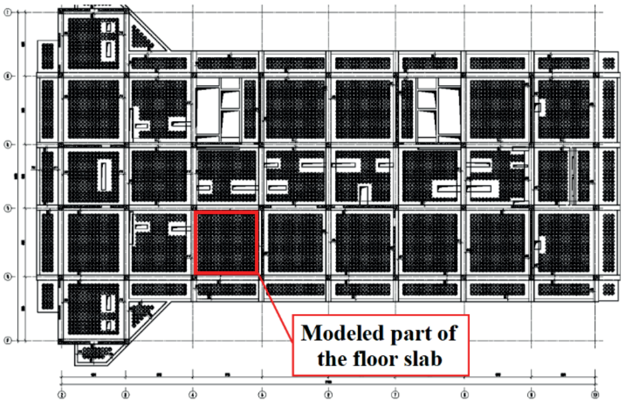


Figure 2. The drawing of a bubbledeck floor slab in the reinforced concrete frame building (a part of the slab chosen for a comparative analysis of various numerical modelling techniques is outlined in red)

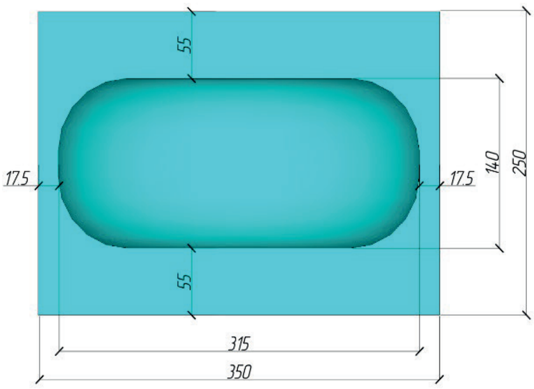


Figure 3. The cross-section of a void former cell used in the considered bubbledeck floor slab

Properties of the considered bubbledeck floor slab material are given in Table 1.

Table 1. Bubbledeck floor slab material properties

Material	Elastic Modulus E, GPa	Poisson's ratio ν	Density ρ, kg/m^3
Concrete B25	30	0.2	2500

The following engineering approaches to numerical modelling of such lightweight structural elements have been considered and compared with the reference and between each other: 1) the void former cell has been considered as a honeycomb structure with top and bottom cover plates which have been all discretized through shell finite elements with effective thickness, density and stiffness; 2) the void former cell has been considered as a homogeneous plate with effective properties, which has been discretized through shell finite elements.

Problem spatial discretization through solid finite elements and the simulation results obtained using such an approach have been taken as a reference. Since only elastic part of the problem has been considered, utilization of the numerical solution as a reference is appropriate, since high accuracy of finite element simulations within the theory of elasticity has been verified multiple times (see, for instance, [1]).

3. FINITE ELEMENT MODELS

The verified ANSYS software [1] has been used for all simulations (a static loading analysis and a modal analysis). In the model assembled for the reference simulations, hexahedral eight node finite elements of the type SOLID185 have been used. In the models, which have been intended to evaluate two different engineering approaches to numerical modelling of bubbledeck floor slabs, quadrilateral four node finite elements of the type SHELL181, in which the Reissner-Mindlin plate theory is implemented, have been utilized.

The whole FE model utilized for the reference simulations and the mesh within the void former cell are illustrated in Fig. 4. The whole model comprises 1 039 247 nodes (three degrees of freedom (DOF) per each node) and 1 056 768 finite elements.

The FE model used to evaluate the first engineering approach to numerical modelling of the bubbledeck floor slab consists of two horizontal layers of plane finite elements connected together through the honeycomb structure also meshed with plane finite elements. A comparison of the void former cell and its approximation through plane structural elements is given in Fig. 5. The whole model and the mesh within the void former cell are illustrated in Fig. 6. The FE model comprises 3 011 nodes (six DOF per each node) and 4 224 finite elements.

The FE model used to evaluate the second engineering approach to numerical modelling of the bubbledeck floor slab is shown in Fig. 7. The model comprises 289 nodes (six DOF per each node) and 256 finite elements. All DOFs (Ux, Uy, Uz, Rotx, Roty, Rotz) of the nodes located at the slab boundaries are restrained. The existence of voids in the floor slab have been simulated through setting effective values of the material density and elastic modulus.

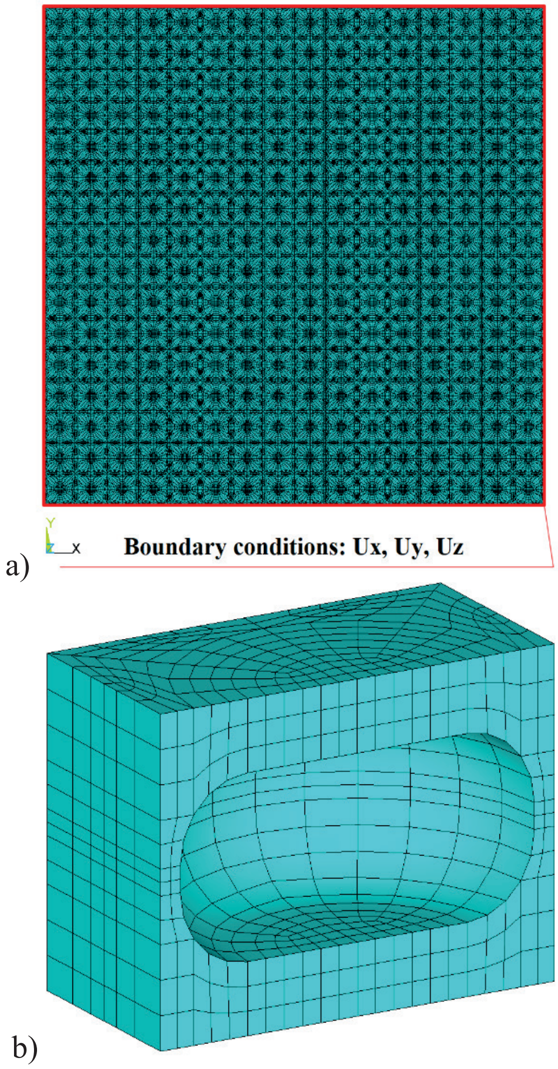


Figure 4. The model of the considered cast-in-place reinforced concrete bubbledeck floor slab meshed with hexahedral finite elements: (a) top view with boundary conditions; (b) mesh within the void former cell

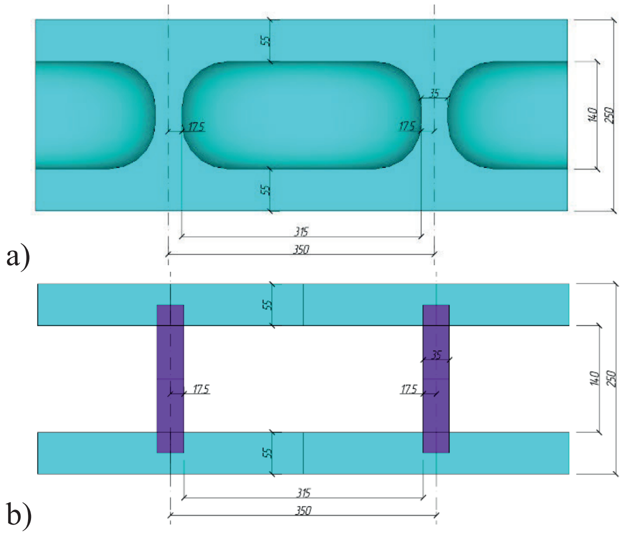


Figure 5. Interrelation between the actual geometry of the bubbledeck floor slab (a) and its approximation through plane structural elements (b) (In the bottom figure different colours correspond to parts with different thicknesses)

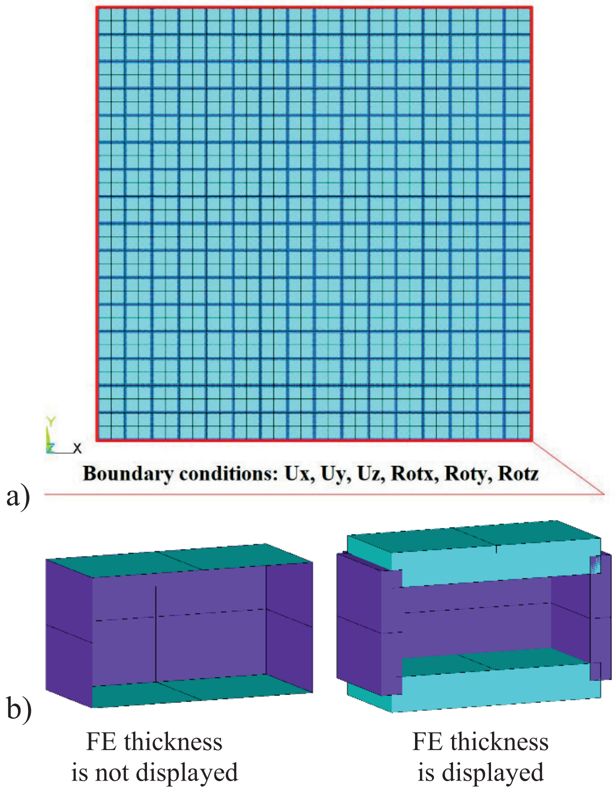


Figure 6. The FE model used to evaluate the first engineering approach to numerical modelling of the bubbledeck floor slab: (a) top view with boundary conditions; (b) mesh within the void former cell

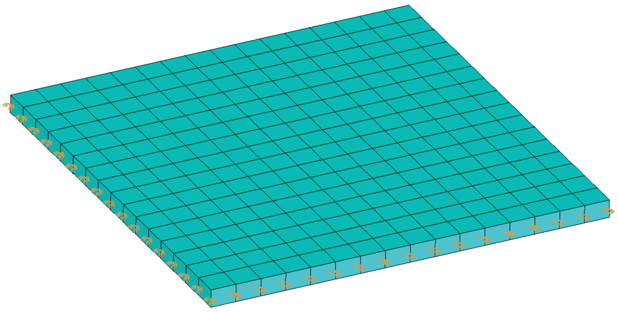
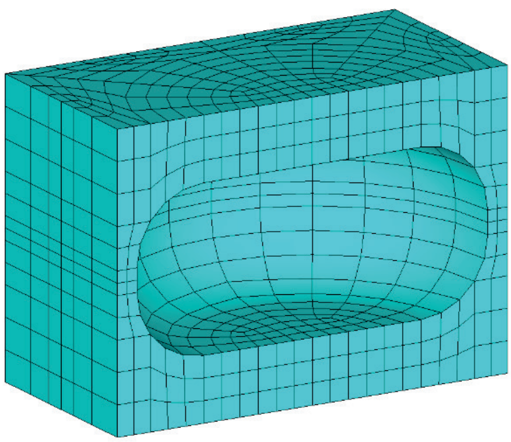


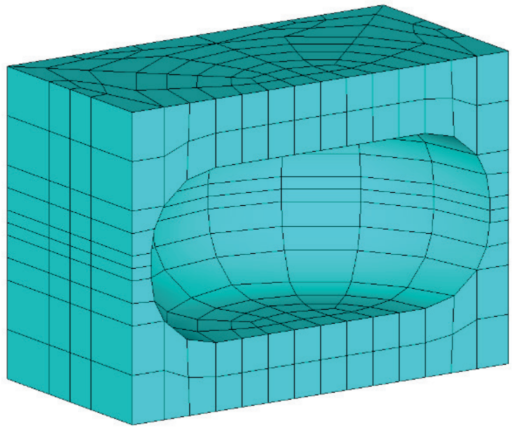
Figure 7. The FE model used to evaluate the second engineering approach to numerical modelling of the bubbledeck floor slab with finite element thickness and boundary conditions displayed

4. MESH SENSITIVITY ANALYSIS

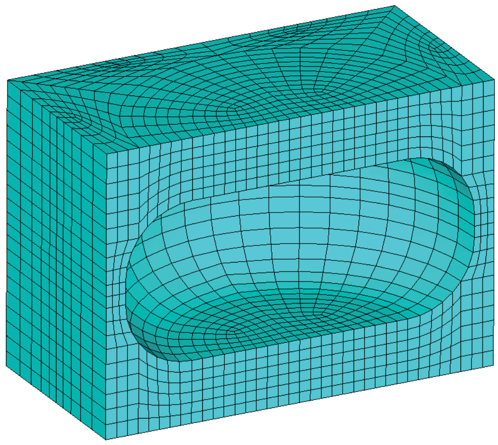
Before conducting simulations with shell finite elements, a mesh sensitivity analysis for the model discretized with solid finite elements had been performed. Three different element sizes had been used to calculate eigenfrequencies and eigenmodes of the considered slab (see Fig. 8). Results of the conducted modal analysis are given in Table 2. As it is seen from Table 2, there is negligible difference between the results obtained using different mesh sizes.



a)



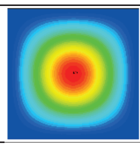
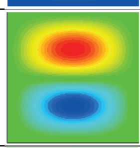
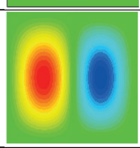
b)

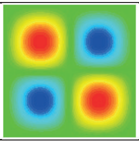
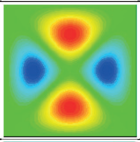
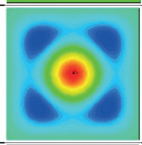
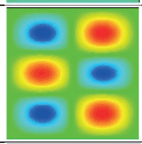
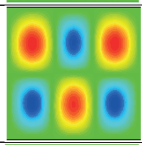
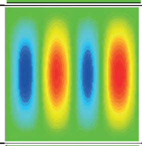
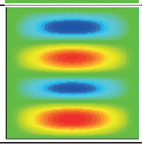


c)

Figure 8. Meshes considered during the mesh sensitivity analysis: (a) reference mesh; (b) coarse mesh (twice as large); (c) fine mesh (1.5 times smaller)

Table 2. Eigenfrequencies and eigenmodes calculated using the reference FE model with different mesh sizes

#	Eigenmode	Reference mesh	Coarse mesh	Fine mesh	Δ, %
		Eigenfrequency, Hz			
1		50.04	50.05	50.03	0.0
2		98.25	98.42	98.2	0.2
3		98.25	98.42	98.2	0.2

4		140.22	140.61	140.05	0.3
5		167.67	168.25	167.53	0.3
6		169.03	169.60	168.89	0.3
7		204.93	205.80	204.61	0.4
8		204.93	205.80	204.61	0.4
9		254.44	255.78	254.08	0.5
10		254.44	255.78	254.09	0.5

5. PARAMETRIC ANALYSIS OF THE ENGINEERING APPROACHES

A parametric analysis of the FE models used to evaluate two engineering approaches to numerical modelling of bubbledeck floor slabs has been performed to determine, which parameters of the problem have a significant influence onto the static and dynamic response of the considered slab and what effective values they should be set to have the static and dynamic response equivalent to that of the reference FE model discretized through solid finite elements.

Three different sets of parameters to variate (denoted as 1A, 1B, and 1C, respectively) have been considered for the first engineering FE model, and one set of parameters to variate (denoted as 2A) has been considered for the second engineering FE model.

The parameters set 1A (see Table 3). The reference density value (see Table 1) of both the horizontal plates and vertical ribs of the first engineering FE model has been increased by a factor of k_ρ = 1.1484 (up to 2871.1 kg/m^3) to equalize the mass of the whole model to that of the reference FE model (which equals 13 634 kg). Then, the elastic modulus of plane vertical elements, which model vertical ribs of the bubbledeck floor slab, have been iteratively changed to the final value of 87 GPa to match the results of the modal analysis obtained with the reference FE model.

Table 3. The parameters set 1A

#	Element	*E*, GPa	*ν*	*ρ*, kg/m^3	*t*, mm
1	Horizontal plate of the floor slab	30	0.2	2871.1	55
2	Vertical rib of the floor slab	87	0.2	2871.1	35

Note: parameters different from the reference ones are colored in blue

The parameters set 1B (see Table 4). To equalize the mass of the whole engineering model to that of the reference one, the thickness *t* of the vertical ribs has been increased by a factor of k_t = 1.5421 (up to 54 mm) with the values of all other parameters being kept equal to the reference ones.

Table 4. The parameters set 1B

#	Element	*E*, GPa	*ν*	*ρ*, kg/m^3	*t*, mm
1	Horizontal plate of the floor slab	30	0.2	2500	55
2	Vertical rib of the floor slab	30	0.2	2500	54

Note: parameters different from the reference ones are colored in blue

The parameters set 1C (see Table 5). To equalize the mass of the whole engineering model to that of the reference one, the thickness *t* of both the horizontal plates and vertical ribs has been increased by a factor of k_t = 1.1483 (up to 63.2 and 40.2 mm, respectively) with the values of all other parameters being kept equal to the reference ones.

Table 5. The parameters set 1C

#	Element	E, GPa	v	ρ, kg/m^3	t, mm
1	Horizontal plate of the floor slab	30	0.2	2500	63.2
2	Vertical rib of the floor slab	30	0.2	2500	40.2

Note: parameters different from the reference ones are colored in blue

The parameters set 2A (see Table 6). The reference density value (see Table 1) of the second engineering FE model has been decreased by a factor of k_ρ = 1.4376 (down to 1739.1 kg/m^3) to equalize the mass of the whole model to that of the reference FE model (which equals 13 634 kg). Then, the elastic modulus of the slab has been iteratively changed to the final value of 24 GPa to match the results of the modal analysis obtained with the reference FE model.

Table 6. The parameters set 2A

#	Element	E, GPa	v	ρ, kg/m^3	t, mm
1	Floor slab	24	0.2	1739.1	250

Note: parameters different from the reference ones are colored in blue

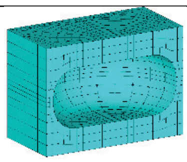
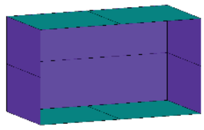
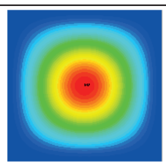
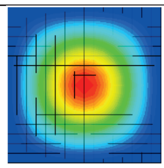
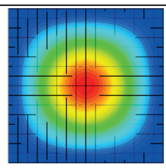
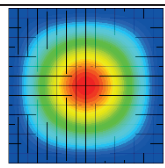
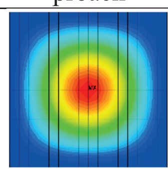
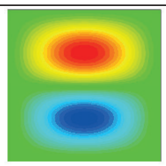
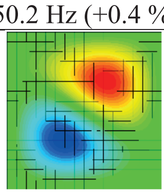
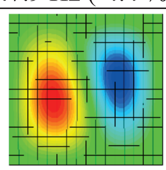
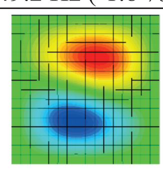
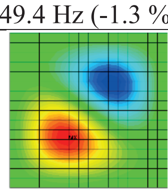
6. SIMULATION RESULTS AND THEIR COMPARISON

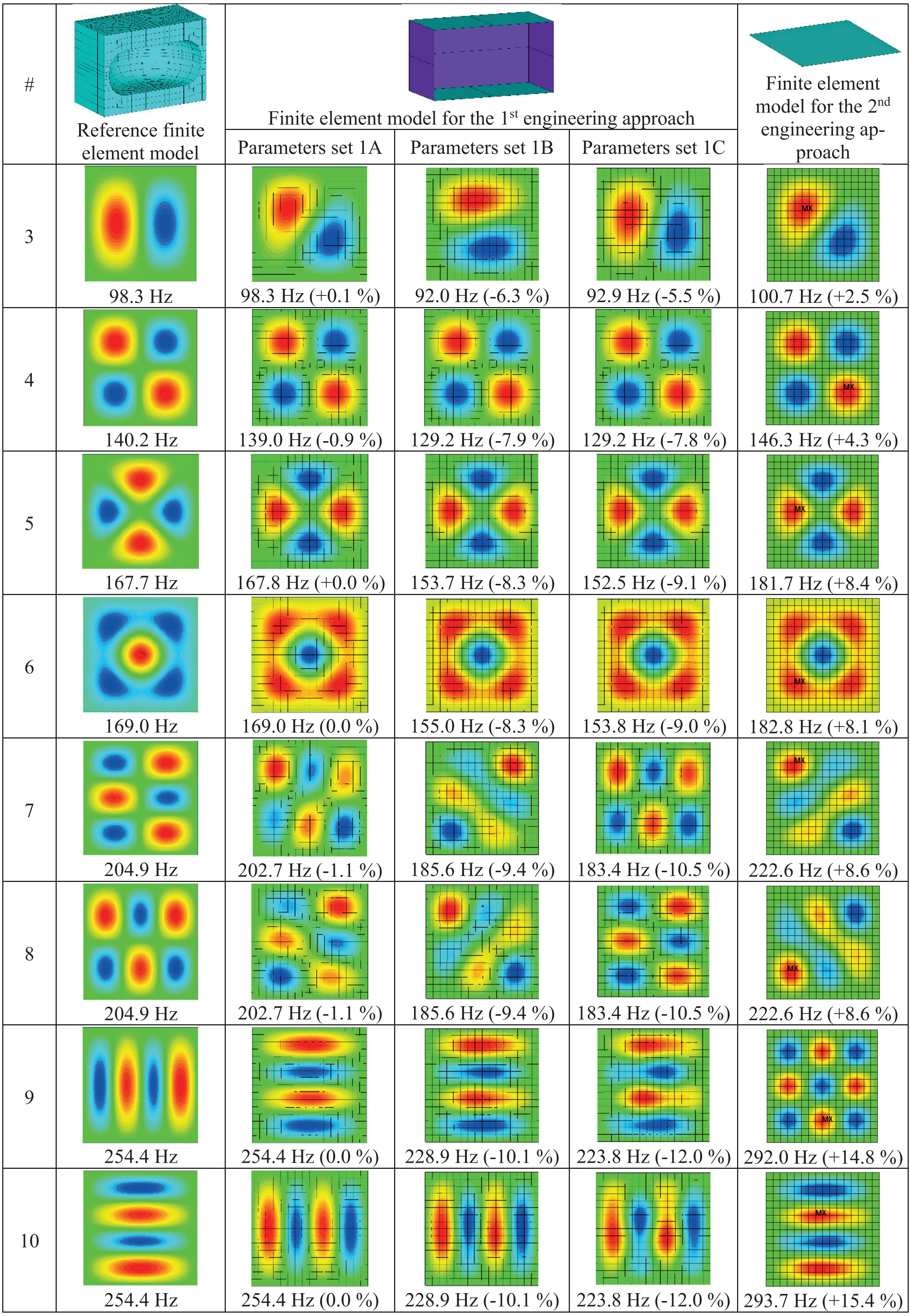
Below in Tables 7-9 and Fig. 9, the simulations results obtained using different FE models are presented and compared with each other.

The results of the modal analysis presented in Table 7 reveal that the best agreement with the reference FE model, in which the spatial discretization of the voided floor slab has been carried out through solid finite elements, has been obtained for the model created within the (first) engineering approach, in which the void former cell has been considered as a honeycomb structure with top and bottom cover plates which have been all discretized through shell finite elements with the values of their parameters given in Table 3.

The results of the static loading of the slab by its dead weight given in Tables 8, 9 and Fig. 9 also show that the FE model created within the first engineering approach with the values of the parameters given in Table 3 yields the closest agreement (both for normal stress and displacements) with the results obtained for the reference FE model constructed using solid finite elements.

Table 7. Results of the modal analysis (In brackets given are the discrepancy, in percent, from the results obtained with the reference finite element model)

#	 Reference finite element model	 Finite element model for the 1st engineering approach			 Finite element model for the 2nd engineering approach
		Parameters set 1A	Parameters set 1B	Parameters set 1C	
1	 50.0 Hz	 50.2 Hz (+0.4 %)	 47.9 Hz (-4.4 %)	 49.2 Hz (-1.8 %)	 49.4 Hz (-1.3 %)
2	 98.3 Hz	 98.3 Hz (+0.1 %)	 92.0 Hz (-6.3 %)	 92.9 Hz (-5.5 %)	 100.7 Hz (+2.5 %)



#	Reference finite element model	Finite element model for the 1st engineering approach: Parameters set 1A	Parameters set 1B	Parameters set 1C	Finite element model for the 2nd engineering approach
3	98.3 Hz	98.3 Hz (+0.1 %)	92.0 Hz (-6.3 %)	92.9 Hz (-5.5 %)	100.7 Hz (+2.5 %)
4	140.2 Hz	139.0 Hz (-0.9 %)	129.2 Hz (-7.9 %)	129.2 Hz (-7.8 %)	146.3 Hz (+4.3 %)
5	167.7 Hz	167.8 Hz (+0.0 %)	153.7 Hz (-8.3 %)	152.5 Hz (-9.1 %)	181.7 Hz (+8.4 %)
6	169.0 Hz	169.0 Hz (0.0 %)	155.0 Hz (-8.3 %)	153.8 Hz (-9.0 %)	182.8 Hz (+8.1 %)
7	204.9 Hz	202.7 Hz (-1.1 %)	185.6 Hz (-9.4 %)	183.4 Hz (-10.5 %)	222.6 Hz (+8.6 %)
8	204.9 Hz	202.7 Hz (-1.1 %)	185.6 Hz (-9.4 %)	183.4 Hz (-10.5 %)	222.6 Hz (+8.6 %)
9	254.4 Hz	254.4 Hz (0.0 %)	228.9 Hz (-10.1 %)	223.8 Hz (-12.0 %)	292.0 Hz (+14.8 %)
10	254.4 Hz	254.4 Hz (0.0 %)	228.9 Hz (-10.1 %)	223.8 Hz (-12.0 %)	293.7 Hz (+15.4 %)

Table 8. Comparison of the vertical displacements due to the slab dead weight

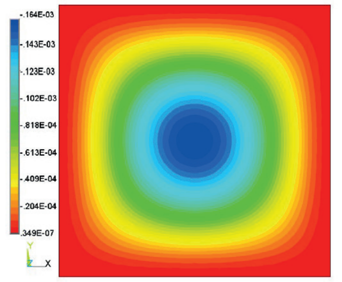
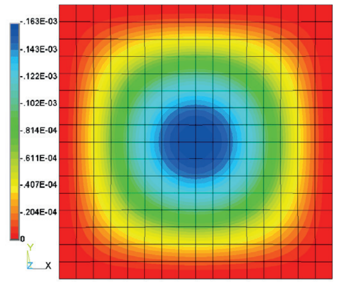
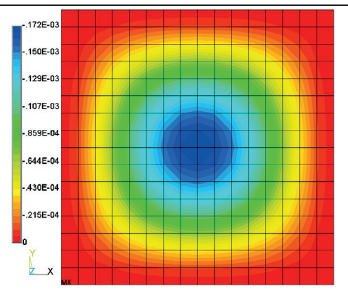
Reference finite element model		Uz_{max} = -0.164 mm
Finite element model for the 1st engineering approach (parameters set 1A)		Uz_{max} = -0.163 mm (-0.6%)
Finite element model for the 2nd engineering approach		Uz_{max} = -0.172 mm (+4.9%)

Table 9. Comparison of the normal stress along X-axis at the top face of the slab in the central cross-section due to the slab dead weight

FE model	Min σ_x, Pa	Δ, %	Max σ_x, Pa	Δ, %
Reference finite element model	-325163	-	904902.1	-
Finite element model for the 1st engineering approach (parameters set 1A)	-306776	-5.7	702694.7	-22.3
Finite element model for the 2nd engineering approach	-275379	-15.3	509014.4	-43.7

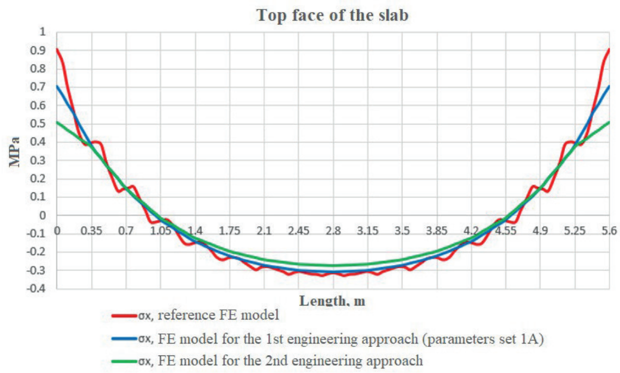


Figure 9. Normal stress along X-axis at the top face of the slab in the central cross-section due to the slab dead weight

CONCLUSION

The following conclusions can be made based on the analysis results and their comparison:

1. As expected, mesh sensitivity of the results obtained for the model meshed with solid finite elements is negligible within the problems of the theory of elasticity, in particular for the modal analysis.
2. The engineering approach to numerical modelling of reinforced concrete bubbledeck floor slabs, within which the void former cell of the slab is modelled as a honeycomb structure with top and bottom cover plates, which are all discretized through shell finite elements with effective density (which has been increased by a factor of 1.1484 relative to the reference one) and stiffness (which has been increased by a factor of 2.9 relative to the reference one for the vertical ribs of the slab), has revealed the best agreement with the results obtained for the slab model meshed with solid finite elements, both for the modal analysis and the static loading analysis. For the first 10 eigenmodes the largest difference in eigenfrequency has been obtained to be 1.1%. The difference in static deflection due to the slab dead weight has been obtained to be 0.6%. The difference in normal stresses at the top face of the slab in the central cross-section has been obtained to be less than 23%.

3. The engineering approach to numerical modelling of reinforced concrete bubbledeck floor slabs, within which the void former cell of the slab is modelled as a homogeneous plate with effective properties, has yielded larger discrepancy with the reference results. For the first 10 eigenmodes the largest difference in eigenfrequency has been obtained to be 15.4%. The difference in static deflection due to the slab dead weight has been obtained to be 4.9%. The difference in normal stresses at the top face of the slab in the central cross-section has been obtained to be less than 44%.

Further research on the subject should be devoted to numerical modelling of bubbledeck floor slabs together with vertical load-bearing structural elements.

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