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Numerical modelling of RC floor slabs

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Abstract. The aim of the paper is to conduct a comparative analysis of four calculation models of reinforced concrete floor slabs, that differ in geometry and the way of supporting. The investigation focuses primarily on the analysis of deflections of cracked reinforced concrete slabs, while monitoring the degree of determined reinforcement and the width of crack opening. The used programs were analyzed in terms of their capabilities, necessary in the work of a modern construction engineer, such as modeling of concrete rheology, determining the real reinforcement, finite element mesh variation, taking into account changes in stiffness of the cracked section, etc. The computational methods used in the software were also taken into account, including the possibility of performing non-linear analysis (mainly in the case of material non-linearity), updating the stiffness matrix (inelastic method) or considering possible stiffening of the concrete under tension. Each model was calculated taking into account the influence of shrinkage and without analyzing it, that required additional analysis of the ways of modeling rheology of concrete with use of computer programs.

1. Introduction

The finite element method (FEM) is currently one of the most commonly used computational methods used for the computer analysis of various structural systems in building construction. Its effectiveness and universality results from the fact that it is possible to replace the analytical problem, which is formulated with differential equations, with an algebraic problem. Three computer FEA programs were used to conduct research on the calculation methods of reinforced concrete slab floors: Autodesk Robot Structural Analysis Professional, Dlubal Software RFEM and ABC Plate.

RC floor slab is one of the structural elements which is extensively used in civil engineering structure. Design of the floor slabs is based on limit states and requires an estimation of the ultimate limit state and knowledge of their deflections and cracking zones. The estimation of deflection under loads is complicated because of the influence of factors like cracking, creep and shrinkage effects.

The main aim of the paper was to conduct a comparative analysis of the calculation of slab floor deflections with reference to the most common software programs used in design offices in Poland. The paper focuses primarily on the analysis of deflections of reinforced concrete floor slabs in the cracking stage, while also monitoring the degree of the determined reinforcement and the crack opening width. The software programs were examined in terms of their capabilities, which are necessary in the work of a modern civil engineer, such as considering concrete rheology, real reinforcement modeling, finite element mesh variation, etc. Attention was also paid to the calculation methods used in the software, including the possibility of performing nonlinear analysis (mainly in the case of material non-linearity), changing the stiffness of the cracking section (elastic method), or taking into account possible hardening of the concrete in tension.

2. Characteristics of used computer programs

2.1. ABC Plate software

ABC Plate software is a product of the Polish company PRO-SOFT and is based on the finite element method that allows the calculation of reinforced concrete floor slabs according to the European standard



PN-EN 1992-1-1: 2008 [1]. ABC Plate software uses linear analysis to calculate given problems, and loads are therefore defined as consecutive simple cases. From the obtained results, further combinations of the superposition method are put together, optionally scaling individual components by increasing factors. ABC Plate software calculates the necessary reinforcement due to the ultimate limit state and determines deflections in the cracking stage. In the case of calculations compatible with the Eurocode, it is also possible to take into account the effects of shrinkage, but only in the analysis of deflections.

2.2. Robot Structural Analysis Professional software

Robot Structural Analysis Professional software of the American company Autodesk uses the finite element method for calculations [2,3]. The software has comprehensive tools for modelling and calculating reinforced concrete structures in the field of linear and nonlinear analysis. However, it should be clearly stated that the material non-linearity assumption does not take into account the change in material stiffness due to on external factors such as temperature. Rheological issues are also not taken into account. However, in the software, the stiffness is updated depending on the cracking of the floor slab, and is adequate to the conditions prevailing in the given node of the plate element (reinforcement ratio, cracking, support conditions).

2.3. Dlubal RFEM software

RFEM software of the German company Dlubal uses the finite element method in the modular structure for calculations [4]. The RF CONCRETE DEFLECT module was used for the analysis of reinforced concrete floor slabs, which allowed calculations in the linear-elastic range and RF CONCRETE NL, which in turn enables non-linear material analysis. The main assumptions of the RF CONCRETE DEFLECT program are calculations of the stiffness of the floor slab element by interpolating between the uncracked and cracked stage, and also consideration the effect of shrinkage and creep on the value of deformations, including deflections. However, the use of the RF CONCRETE NL module makes it possible to perform calculations in a non-linear range when determining deformations, crack opening width and internal forces.

3. Characteristics of the analyzed models of floor slabs

In order to compare the engineering possibilities and computational methods of the adopted computer software, it was decided to subject them to a determination of deflections of reinforced concrete slabs in the cracking mode, while also monitoring the degree of determined reinforcement and crack opening width.

Four different calculation models were used, and they are characterized in detail below. Each of the floor slab models was calculated while taking into account shrinkage without impact, which required analysis of the ways of modelling concrete rheology by the used computer software. Table 1 presents the material data and computational characteristics of the analyzed floor slab models. Table 2 shows load cases and load combinations.

Table 1. The material data and computational characteristics of the analysed floor slabs.

| General | |
|------------------------|---------------|
| Floor slab thickness | 200 mm |
| Admissible crack width | 0,3 mm |
| Mesh size of element | 0,1 m x 0,1 m |
| Concrete | |
| Concrete class | C25/C30 |
| Environment class | XC1 |
| Cement class | N |
| Structure class | S4 |
| Reinforcement cover | 30 mm |
| Reinforcing steel | |

| | |
|---|------------|
| Reinforcing steel | B500SP |
| Steel ductility class | C |
| Minimum diameter of reinforcing steel | 12 mm |
| Rheology of concrete | |
| Concrete age (first loading moment) | 90 days |
| Relative environment humidity | 40% |
| Time calculation for the creep | 18250 days |
| Time calculation for the shrinkage | 18250 days |
| Concrete age at the moment of shrinkage start | 14 days |

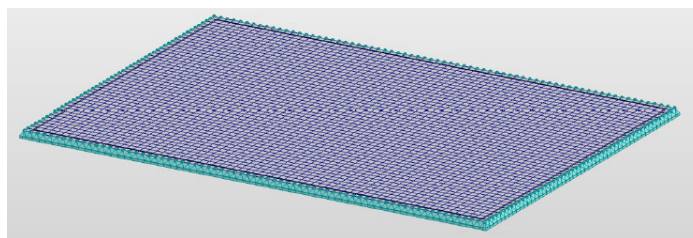
Table 2. Load cases and combinations.

| Load case | Load type | Characteristic value of load (kN/m ²) |
|-------------------|----------------------------|--|
| P1 | Self weight | Automatically included in the computer program 5 |
| P2 | Life load with category C3 | |
| Loads combination | Limit state | Combination formula |
| K1 | Ultimate Limit State | $1,35 \cdot P1 + 1,50 \cdot P2$ |
| K2 | Serviceability Limit State | $1,00 \cdot P1 + 1,00 \cdot P2$ |

3.1. Numerical models of reinforced concrete floor slabs

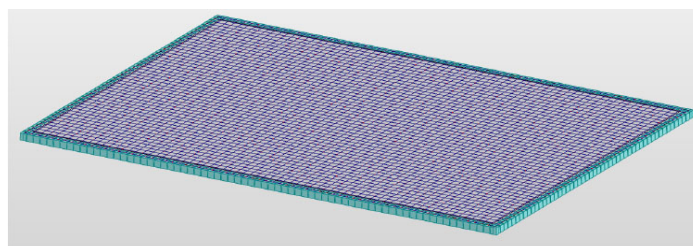
Model M1

The floor slab modelled in rectangle plan as a 5m x 7m, pivotally supported on all four edges, figure 1.

**Figure 1.** Geometry and boundary conditions of model M1.

Model M2

The floor slab modelled in rectangle plan as a 5m x 7m, fixed supported on all four edges, figure 2.

**Figure 2.** Geometry and boundary conditions of model M2.

Model M3

The floor slab modelled in rectangle plan as a 5m x 7m, fixed supported on one short edge and pivotally supported on two longer edges, figure 3.

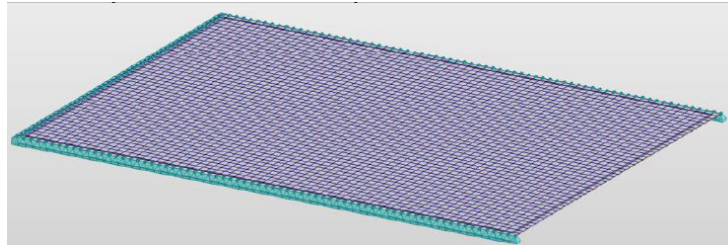


Figure 3. Geometry and boundary conditions of model M3.

Model M4

The floor slab modelled in rectangle plan as a 8m x 12m, pivotally supported on all four edges and additionally supported on a reinforced concrete binder of 0.3m x 0.4m made of C25 / 30 concrete and placed in 1/3 and 2/3 of its span, figure 4. The beams were offset, in relation to the center of gravity of the floor slab, in such a way that the slab lay on them and an eccentric connection between the elements was formed. The Binders were modelled as rods with reinforced concrete beam characteristics.

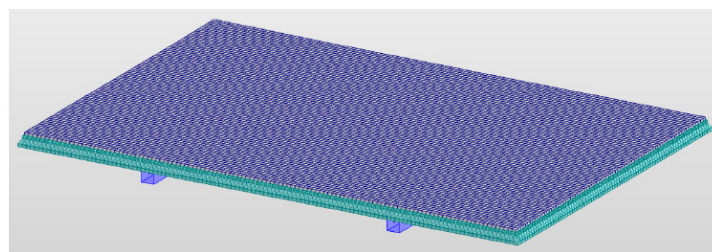


Figure 4. Geometry and boundary conditions of model M4.

4. Methods of rheology modeling in numerical analysis

4.1. Creep

Concrete creep is a phenomenon related to the deformation increase caused by constant long-term stress. It is mainly visible when the element has a guaranteed freedom of deformation. An important factor is the fact that the increase in deformation is caused by creep decreases with the passage of time. The effect of the phenomenon depends, among other things, on the class of concrete, its composition, age at the first loading moment and environmental conditions - mainly humidity and temperature [5]. All the applied software programs included the influence of the creep on the structure of the analysed floor slabs, Tab. 3.

Table 3. Creep coefficient value for the analysed floor slab models .

| Software | RFEM | ROBOT | ABC PLATE |
|-----------------------|-------|-------|-----------|
| The creep coefficient | 2,294 | 2,315 | 2,295 |

4.2. Shrinkage

Concrete shrinkage is a phenomenon consisting of intrinsic rheological deformations that are not related to mechanical loads. It is caused by structural changes occurring in the cement paste as a result of the physico-chemical processes of water loss as a result of the setting, hardening and drying of concrete. Total deformation due to shrinkage is the sum of two components: autogenous shrinkage and drying.

4.2.1. ABC Plate software

ABC Plate software only takes into account the effect of shrinkage when defining the deflection curve of elements. With this phenomenon, an additional deflection curvature is created, which should be taken into account when determining the total vertical deformation. In the case of cracked floor slabs, the slab deflection will occur towards the tension zone due to gravitational loads. ABC Plate software enables the adding of total deflections that are determined on the basis of assumed loads.

4.2.2. Robot Structural Analysis Professional software

Robot Structural Analysis Professional software does not take into account the influence of shrinkage in the designing of RC elements, even in the range of the serviceability limit state. Therefore, it is necessary to model the effects of shrinkage using the equivalent of another interaction, which would lead to similar stresses in the element. The effect of shrinkage in RC structures can be seen to be equivalent to lowering the temperature by 15°C, and this method was used to model this phenomenon with the Robot Software. It should be taken into account that shrinkage modeled in this way is only an approximation, and results in a significant overdesigning of the structure. In fact the factors of deformation and strength of concrete that are variable over time are not taken into account. Moreover, an important issue in this type of modelling is that the temperature effect is taken into account as in an isotropic, linear-elastic material, which corresponds to the uncracked concrete structure [6]. The flexural stiffness of the analyzed cross-section is decreased at the moment crack appears, and this results in a lowering of the internal forces. This assumption leads to a significant over-designing of the structure and the determination of reinforcement which exceeds the required reinforcement. The issue is visible in the numerical analysis of reinforced concrete floor slabs, where the consideration of shrinkage in Robot Software resulted in significant additional reinforcement of the structure.

4.2.3. Dlubal RFEM software

Dlubal RFEM software takes into account the effect of shrinkage in the *RF CONCRETE NL* and *RF CONCRETE DEFLECT* modules by reducing the stiffness of the material and applying the distribution factor. Stiffness of the material in any ϕ direction of reinforcement is reduced by the coefficient of influence of shrinkage $k_{sh,\phi,c}$. The longitudinal axial force and bending moment are only determined for shrinkage deformation in both cracked and uncracked conditions.

$$n_{sh,\phi} = -\varepsilon_{sh} \cdot E_s \cdot (a_{s1} + a_{s2}), \quad (1)$$

$$m_{sh,\phi} = n_{sh} \cdot e_{sh}, \quad (2)$$

where:

$n_{sh,\phi}$ - additional axial force from shrinkage in the ϕ -direction of reinforcement;

$m_{sh,\phi}$ - additional bending moment from shrinkage, defined for the center of gravity for the ideal cross-section, in the ϕ -direction of reinforcement;

a_{s1} - bottom surface of reinforcement;

a_{s2} - top surface of reinforcement;

E_s - Young's modulus for steel;

ε_{sh} - shrinkage deformation;

e_{sh} - eccentricity of shrinkage forces.

For internal forces determined in this way due to shrinkage, the additional curvature induced by these forces is calculated at the analysed point without any additional external forces.

Then the new coefficient $k_{sh,\phi,c}$ is determined as follows:

$$k_{sh,\phi,c} = \frac{\kappa_{sh,\phi,c} - \kappa_\phi}{\kappa_\phi}, \quad (3)$$

where:

$\kappa_{sh,\phi,c}$ - curvature caused by external loads without the influence of shrinkage on the ϕ -direction reinforcement;

κ_ϕ - curvature caused by shrinkage (and reinforcement arrangement) without the influence of creep on the ϕ -direction reinforcement.

4.2.4. Distribution coefficient

Distribution coefficient is used to account for concrete hardening in tension. Its calculation is initially carried out with the assumption of a linear-elastic behaviour. In this case the maximum stresses in the concrete, taking into account shrinkage can be written in the following form:

$$\sigma_{max,\phi} = \frac{n_\phi + n_{sh,\phi}}{A_{phi,l}} + \frac{m_\phi - n_\phi \cdot \left(x_{\phi,l} - \frac{h}{2}\right) + m_{sh,\phi,l}}{I_{\phi,l}} \cdot (h - x_{\phi,l}). \quad (4)$$

where:

n_ϕ - axial force from the external load in the ϕ -direction of reinforcement;

$n_{sh,\phi}$ - an additional axial force from shrinkage in the ϕ -direction of reinforcement;

m_ϕ - bending moment from the external load in the ϕ -direction of reinforcement;

$m_{sh,\phi,l}$ - an additional bending moment from shrinkage in the ϕ -direction of reinforcement;

$x_{\phi,l}$ - height to the neutral axis of the uncracked cross-section in the ϕ -direction of reinforcement;

h - height of cross-section in ϕ -direction of reinforcement;

$A_{phi,l}$ - cross sectional area in uncracked stage in the ϕ -direction of reinforcement;

$I_{\phi,l}$ - moment of inertia of the cross-section in uncracked stage in the ϕ -direction of reinforcement.

Distribution coefficient can be written as:

$$\xi = 1 - \beta \cdot \left(\frac{f_{ctm}}{\sigma_{max,\phi}} \right)^n \quad (5)$$

where:

β - coefficient depending on the effect of the load term or the influence of repetitive loads on average strain;

$$\xi = 0 \text{ for } \sigma_{max,\phi} \leq f_{ctm} \quad (6)$$

$\xi = 1$ - without taking into account hardening in tension.

5. Numerical analysis of floor slabs

The procedure for determining the required reinforcement by using analyzed software was carried out after accepting the same material and computational assumption given in Table 1,2. The calculations were carried out for two cases, without the influence of shrinkage and by modelling its impact. On this basis, the minimum reinforcement of the floor slab and the required reinforcement that should be adopted to fulfil standard conditions were obtained. The results of these calculations were related to the results obtained in the Robot software (reference software). After determining the provided reinforcement in the Robot Structural Analysis software for each calculation model (M1, M2, M3, M4) which correspond to the demand due to ULS and SLS and at regular arrangement, the obtained reinforcement was introduced to the other two software models: ABC Plate and Dlubal RFEM. This procedure aimed to compare the deflection results in the next step. When analyzing the serviceability limit state, attention should be paid to cracking of the reinforced concrete floor slab. The formation of a crack is connected with reaching the ultimate tensile strength. According to the current standard (PN-EN 1992-1-1), the crack width should be limited to a level that does not impair the functioning or durability of the structure and nor make the appearance of the element unacceptable. In order to unify the method of selection of additional reinforcement against excessive cracks, the limit admissible crack width in all the analyzed software was set as $w_{k,max} = 0.3mm$.

The Dlubal RFEM and Robot Structural Analysis software give the obtained results depending on the analyzed plane of the floor slab (upper or lower) and the main directions of the determined reinforcement. The ABC Plate software is limited to only providing results for the upper and lower level of the floor slab. One of the main conditions of the serviceability limit state that all structural elements must fulfill, and above all, floor slabs, is that the permissible deformations, including deflections, are not exceeded. When designing, the analysis of deflections of cracked floor slab determines their thickness and its reinforcement. The basic parameter which should be defined is the value of permissible deflection.

Table 4. The maximum deflection of the analysed calculation models.

| Model | Span L (mm) | Limit criterion | maximum deflection f (mm) |
|-------|-------------|-----------------|------------------------------|
| M1 | 7000 | L/250 | 28 |
| M2 | 7000 | | 28 |
| M3 | 7000 | | 28 |
| M4 | 8000 | | 32 |

5.1. Algorithms for calculation of deflections in floor slabs

5.1.1. ABC Plate software

- Local stiffness method

This method consists of calculating the curvature in cross-sections that are densely distributed along the element, and then on defining the deflection by numerical integration. Static calculations are performed for a particular load scheme with the same assumptions made as for the elastic plate. As a result, the values of internal forces in the form of bending moments in each finite element of the structure are obtained. On the basis of the previously adopted reinforcement and internal acting forces, the flexural stiffness of the cross-section is determined independently in each direction of reinforcement. The algorithm recalculates the floor slab for the assumed load scheme, however, it takes into account the determined flexural stiffnesses in both directions in the finite elements. As a result, a new distribution of internal forces is obtained in the form of bending moments, and a re-determination of independent flexural stiffnesses is obtained with the assumed reinforcement, but with new values of moments. The algorithm is repeated until the difference between consecutive values of maximum deflections is minimal.

5.1.2. Robot Structural Analysis software

- Method of updating stiffness (FEA)

In this algorithm, after determining the required reinforcement for the ULS and SLS standard requirements, the software determines the appropriate stiffness for all finite elements of the structure, independently in both directions. Then, the weighted average of both stiffness values is determined, where the weight is the ratio of the acting bending moments.

$$B_{x,y} = c_f \cdot B_x + (1 - c_f) \cdot B_y \quad (7)$$

where:

B_x, B_y - real stiffnesses calculated for two reinforcement directions;

c_f - weight factor, calculated from the formula, depending on the value of the ratio of bending moments.

The effect of using the above formulas is the fact that in the case of a large difference between bending moments in both directions, the stiffness in the orientation of the action of the larger one is assumed in the calculations. The ratio of elastic stiffness D to the average weighted stiffness B is calculated according to the formula below and should be less than one.

$$\left(\frac{D}{B}\right)_{x,y} = \frac{D}{c_f \cdot B_x + (1 - c_f) \cdot B_y} \quad (8)$$

where:

$$D = E \cdot I \quad (9)$$

The final stiffness ratio, which is taken to determine the total deflections of the analyzed floor slabs, is obtained from averaging the average stiffness ratio and stiffness ratio of the element, where extreme values of bending moment were determined in any direction. These values have additional weights with coefficients of 0.25 and 0.75, respectively.

$$\left(\frac{D}{B}\right) = 0,25 \cdot \left(\frac{D}{B}\right)_{x,y} + 0,75 \cdot \frac{D}{B(M_{max})} \quad (10)$$

5.1.3. Dlubal RFEM software

- Algorithm of the *RF CONCRETE DEFLCT* module

For elements subjected to bending, the deformation can be determined as follows:

$$\alpha = \xi \cdot \alpha_{II} + (1 - \xi) \cdot \alpha_I \quad (11)$$

where:

α - is a deformation parameter;

α_I - the value of deformation in uncracked stage;

α_{II} - the value of the deformation in the cracked stage;

ξ - distribution coefficient, used to account for hardening in tension.

$$\xi = 1 - \beta \cdot \left(\frac{\sigma_{sr}}{\sigma_s}\right)^2 \quad (12)$$

where:

$\xi = 0$ for uncracked sections; $\xi = 1$ for fully cracked section;

β - coefficient depending on the influence of the term load or the impact of the repetitive load on the average strain;

σ_s - stresses in tensile reinforcement, calculated on the assumption that the cross-section is fully cracked;

σ_{sr} - stress in tensile reinforcement, calculated on the assumption that the cross-section is fully cracked, which is caused by the load initiating the cracking.

According to eq. (11), the deformation ε_ϕ and the curvature of the deflection κ_ϕ are determined by interpolation between a cracked and uncracked stage:

$$\varepsilon_\phi = \xi_\phi \cdot \varepsilon_{\phi,II} + (1 - \xi_\phi) \cdot \varepsilon_{\phi,I} \quad (13)$$

$$\kappa_\phi = \xi_\phi \cdot \kappa_{\phi,II} + (1 - \xi_\phi) \cdot \kappa_{\phi,I} \quad (14)$$

5.2. Comparative analysis of calculated deflections

After determining the provided reinforcement in the Robot Structural Analysis reference software, the obtained results, in the form of bars of a fixed diameter and at an assumed spacing, were modeled in the other two calculation software models: ABC Plate and Dlubal RFEM.

For each considered computational model, two cases were analyzed: including shrinkage and without taking shrinkage into account. Then, individually in all the programs, the maximum deflection value of the floor slab was determined.

Within one software model, the available calculation methods were used, which differed depending on the system selection.

Based on the results obtained in all the analyzed calculation models, can be noticed that deflections in the *Robot Structural Analysis* program are smaller when using the non-elastic method (with updating the stiffness matrix) than in the simplified elastic method when assuming an average elasticity of the

material of 20-40% . This is due to the fact of the taken into account partial hardening in tension. These differences are clearly visible in the M4 model, where the deflection values, taking into account the update stiffness, are half as much as in the case of the equivalent stiffness method. This results from the use of additional spring supports in the form of binders, as seen in Table 5.

Table 5. Comparison of elastic and non-elastic methods to determine deflection.

| Model M4 | Elastic Method | Non-elastic Method |
|-------------------------|----------------|--------------------|
| maximum deflection (mm) | 31,33 | 14,71 |

Particular attention should be paid to the comparison of deflection results in various computer programs, in particular in relation to those obtained with regard to shrinkage. In simple models M1-M3 (figure 5,6,7), where there are no additional cross-beams, the convergence of the results of Robot Structural Analysis and *ABC Plate* software can be seen.

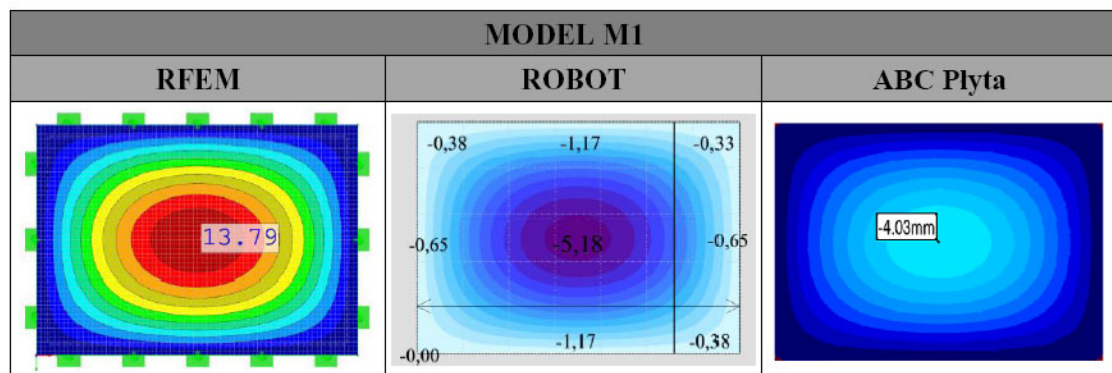


Figure 5. Maps of deflection considering the shrinkage effect for the M1 model obtained in the applied software.

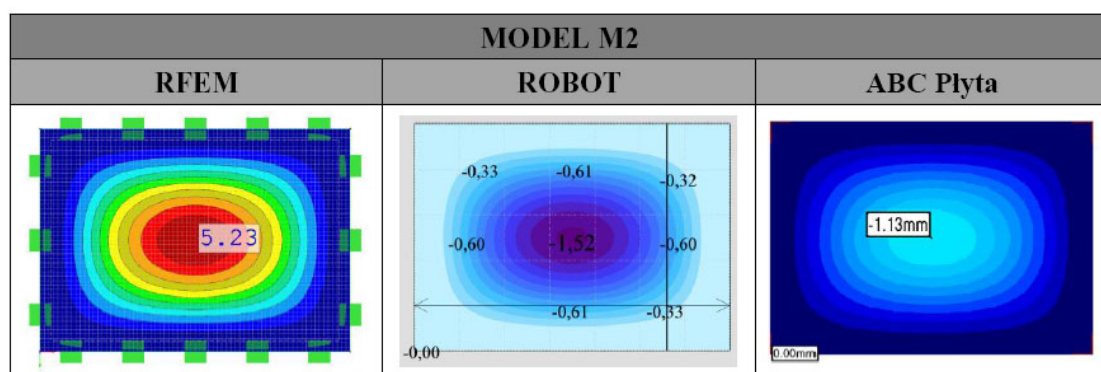


Figure 6. Maps of deflection considering the shrinkage effect for the M2 model obtained in the applied software.

In relation to the *Dlubal RFEM* software, these values differ significantly, which is caused by the lack of a clear way to define shrinkage deformations.

There are similar deflection values for Dlubal RFEM and ABC Plate software in the M4 model (figure 8), whereas the determined deflection in *Robot Structural Analysis* differs by 17-28%. This difference is caused by a different way of modelling the binder, and also by its impact on the analyzed floor slab.

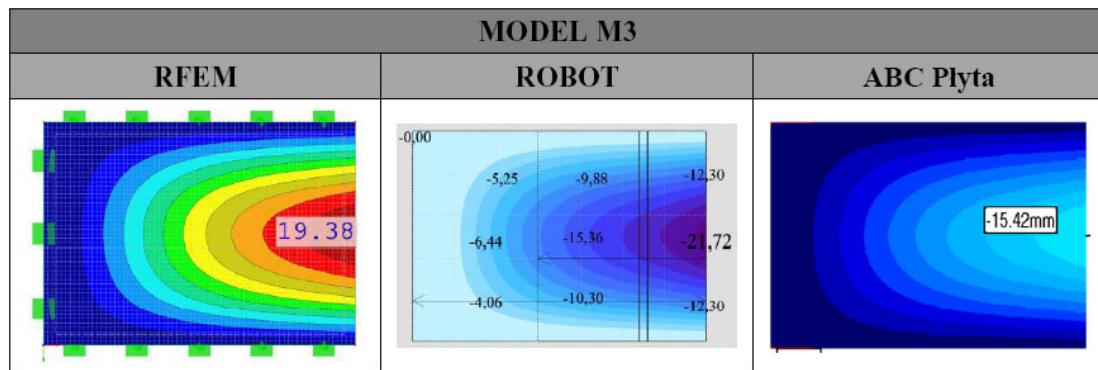


Figure 7. Maps of deflection considering the shrinkage effect for the M3 model obtained in the applied software.

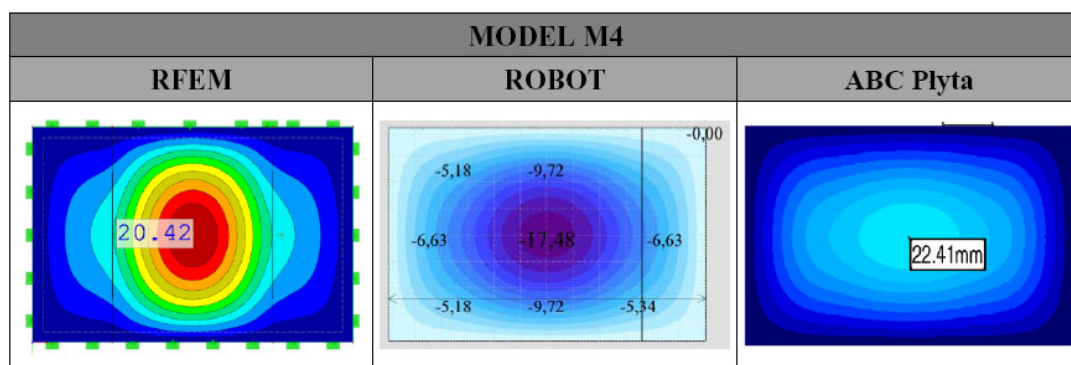


Figure 8. Maps of deflection considering the shrinkage effect for the M4 model obtained in the applied software.

6. Summary

By performing calculations with three leading computer programs (*Robot Structural Analysis*, *ABC Plate and Dlubal RFEM*), which are available in design offices in Poland, many problems resulting from their use were found. Despite the fact that these software programs are based on FEA and have the same iterative algorithm of the incremental Newton-Raphson method used in non-linear analysis, the obtained deflection results differ significantly. This is all the more interesting because the analyzes were carried out in accordance with the procedure described in the applicable standards. An important issue that appeared during the modeling of a reinforced concrete slab was the way of describing rheological phenomena and their inclusion by various computer programs. The effect of shrinkage and creep has a significant impact on the cracking and deflections of concrete elements. Large value of shrinkage and creep which is experienced by materials of slab structure will be one of the factor which cause enormous deflection. While the analysis of the impact of creeping proved to be consistent for all the software programs (it consisted of determining the creep coefficient, which then reduced the modulus of elasticity of the concrete), so the adoption of shrinkage effects was definitely different. The *ABC Plate* software takes into account the effect of shrinkage, but only when defining the deflection curve of elements. *Robot Structural Analysis* software does not take into account the influence of shrinkage in the designing of reinforced concrete elements, even in the range of the serviceability limit state, and its effect in reinforced concrete structures can be taken to be equivalent to a temperature reduction of 15°C. However, *Dlubal RFEM* software takes the impact of shrinkage on the designed concrete element into full account, both in the area of linear and non-linear analysis.

Differences in results are appeared when determining the minimum reinforcement in computational programs. This resulted from different interpretations of the standard recommendations, where it was

not specified when exactly the minimum reinforcement should be taken into account when analyzing the serviceability limit state. In the *ABC Plate* algorithm, each numerical calculation is defined as an exact analysis, whereas *Dlubal RFEM* considers it only those made using the non-linear method. Computer programs use linear and nonlinear analyzes to determine the effects of various factors. When analyzing reinforced concrete slabs, the material nonlinearity taking into account the behavior of specific materials during loading is decisive. The impact of the use of nonlinear analysis is most clearly visible in the *Dlubal RFEM* software and its *RF CONCRETE DEFLECT* and *RF CONCRETE NL* modules. This software was the only one of the analyzed programs which, has an algorithm that uses non-linear analysis that includes shrinkage. The use of this type of analysis resulted in significantly higher crack values and a different distribution and direction of the cracks (rotational cracking model). Differences in the applied analyzes can also be observed in the determination of deflections, where lower results were obtained in the case of nonlinearities, due to the consideration of hardening in tension with residual concrete strength. Summing up, it should be stated that the conducted numerical analyses, which are related to the determination of deflections in various models of floor slabs, require correction and confirmation by experimental methods on real structures. However, the numerical analysis carried out by the authors, which takes into account many material aspects, is necessary for the correct estimation of slab floor deflections. The next stage of the analyzes of deflections of reinforced concrete floor slabs will be experimental research.

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