Experimental study of flat reinforced concrete slabs created in the method of early striking

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Abstract. This report examines the behaviour of an experimental two-storey monolithic construction during the construction of its flat slabs with a formwork system suitable for the application of early striking. The experimental results of the deformations in the slabs are compared with those from the numerical model of the construction. The peculiarities in the findings of the strength characteristics of the concrete used for the monolithic structure in the tests are analysed. Conclusions are made regarding the production of reinforced concrete slabs through formwork systems suitable for early striking from these results and comparisons.

1. Introduction
The method of Early striking is becoming more and more popular in modern building. The principle of early striking is based on the technology for propping or re-propping the main field of a slab with shores, which divide it into smaller fields, which in turn requires overcoming smaller bending moments and shear forces in the partly stroked slab. When using formwork systems for Early striking, it is possible to striking a large part of the formwork elements as early as 2-3 days after laying the concrete in the slab. Only part of the shores with the adjacent dropheads remain. Technically and economically, this is a good solution for the construction of buildings and structures [1], [2]. This technology, in turn, has its peculiarities. There are many studies on this issue worldwide. Some of these studies research the issue of the transfer of loads to reinforced plates by shores to others below them also propped by shores and which have not yet reached their full strength characteristics. As well as to these plates, which are completely strucked and have reached their full strength characteristics. Some of the authors who have studied this problem numerically and experimentally are [3], [4], [5], [6]. Other authors [7], summarize the research done in the second half of the XX century and those in the XXI century. Other studies have examined the conditions that a reinforced concrete slab must meet to be produced using the Early Striking method [8], [9]. Some studies also address globally the problem of early loading of reinforced concrete slabs by loads arising from the production of buildings and structures, [10]. Generally, several main peculiarities that need special attention when applying the method of early striking.

2. Object and tasks in the study
The object of the report is to present an experimental study on the behavior of an experimental construction with two flat reinforced concrete slabs produced with a frame formwork system with dropheads for Early striking. Also to identify the main issues and peculiarities in the application of the method, which should be taken into account when using the technology of early striking in the production of reinforced concrete slabs. The tasks in the report are - measuring the deflections of the
two slabs of the experimental construction in the different stages of striking and loading, comparing the deflections in the slabs with the elastic ones obtained from a numerical model of the structure and tracking the cracks in the slabs in the stages of construction, and analyzing the results.

3. Experimental construction
The report examines an experimental two-storey reinforced concrete construction with two beamless slabs. The dimensions of the slabs are 125 cm wide and 550 cm long. The height of the construction is 232 cm. The foundations are 160x60cm in size and 30cm high Figure 1. The concrete used for the construction is C20/25. The shores used between the two slabs in the formwork system are adapted for small inter-floor heights (about 1m). The shores with adjacent dropheads, under the two slabs, are placed longitudinally in the middle of the slabs, and the axial distances between the shores and columns are shown in Figure 4. For clearer measurement results, the thicknesses of the reinforced concrete slabs of the structure are 16 and 14 cm, respectively, and the reinforcement embedded in them is close to the minimum reinforcement coefficient. The loads in the slabs are of their weight, the load from the formwork system for the second slab and simulated loads during construction used in some of the stages of construction. The additional simulated loads are from formwork panels weighing 200 kg, which sit on a second plate, and simulate the load of pallets weighing 1422 kg, which steps linearly on a second slab Figure 4. The deflections in the slabs are measured by dial gauges attached to a metal frame between the slab of level +1.21 (first slab) and the slab of level +2.32 (second slab) separate from the construction.

Figure 1. Formwork plan of experimental structure.

Figure 2. Stage of building structure.

Figure 3. Stage of simulating loading.

4. FE model of experimental construction
The numerical model of the construction is made with software based on FEM. For the modeling of the slabs, a two-dimensional slab finite elements are used, and the reinforced concrete columns and metal shores - are modeled with beam finite elements [11]. The shores were modeled with a composite section with dimensions such as those used in the experiment – two metal tube sections (inner and external) with a length of 50 cm, the external tube with a diameter of 60 mm and a thickness of 2 mm, the inner with a diameter of 50 mm and a thickness of 1.7 mm. The adjustable thread, ring, and pin for shore height adjustment are not taken into account and are not modeled. The column-slab node and the shores-slab node are modeled as simple joint connections. The load from the formwork system and the temporary loads placed on the slabs are modeled as point and linear loads. For each of the days, the actual values of the elastic modulus obtained from laboratory tests are entered.

5. Experimental study
The study traced the deflections and cracks in the slabs. The study was performed in 15 steps shown in Figure 4. In each step, the level of casting and striking, the corresponding additional load, the age of the
concrete of the first slab \( t_1 \), axial distances (cm) between shores, columns and additional loads, and the elastic modules for the respective age of the concrete of each slab \( E_1, E_2 \) are shown. There are 9 stages of the construction, and the steps included in the separate stages are listed in Table 1.

5.1. Steps:

| Stage | Step | Period (days) | Time (days) | Actions |
|-------|------|---------------|-------------|---------|
| 1     | 1-2  | 4<sup>th</sup> | 1           | Cleaning 1<sup>st</sup> slab |
| 2     | 3    | 4<sup>th</sup> - 7<sup>th</sup> | 3           | Casting 2<sup>nd</sup> slab |
| 3     | 4    | 7<sup>th</sup> | 1           | Laying 2<sup>nd</sup> slab |
| 4     | 4-5  | 7<sup>th</sup> - 11<sup>th</sup> | 4           | Cleaning 2<sup>nd</sup> slab and striking 1<sup>st</sup> slab |
| 5     | 5-8  | 11<sup>th</sup> | 0.5         | - |
| 6     | 9-10 | 11<sup>th</sup> - 14<sup>th</sup> | 3.5         | Loading 2<sup>nd</sup> slab with temporary load |
| 7     | 11   | 14<sup>th</sup> | 0.5         | Unloading the temporary additional load |
| 8     | 12   | 14<sup>th</sup> | 0.5         | Loading 2<sup>nd</sup> slab with temporary load |
| 9     | 13-15| 15           | 1           | Removing the additional load and striking 2<sup>nd</sup> slab |

5.2. Stages:

**Table 1. Stages of the constructive process.**

**Figure 4.** Constructive process.
6. Results and discussion

The values of the elastic deflections (Elastic Zo), the experimental measurements of the vertical deflections (Exp. Zo), and the cracks in the slabs are presented in Table 2 and Table 3.

6.1. Elastic deflections from numerical model (mm)

Table 2. Elastic deflections in each of the points.

| Day, t1st slab | Step | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 4th (1) day   | 1    | 0.08| 0.06| 0.08| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 4th (2) day   | 2    | 0.15| 0.31| 0.15| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 7th (1) day   | 3    | 0.19| 0.38| 0.19| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 7th (2) day   | 4    | 0.32| 0.67| 0.32| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 11th (1) day  | 5    | 0.27| 0.52| 0.27| 0.00| 0.00| 0.37| 0.54| 0.37| 0.00| 0.00|
| 11th (2) day  | 6    | 0.27| 0.46| 0.27| 0.00| 0.00| 0.41| 0.71| 0.41| 0.00| 0.00|
| 11th (3) day  | 7    | 1.63| 1.47| 0.47| 0.00| 0.00| 0.67| 1.70| 1.67| 0.00| 0.00|
| 11th (4) day  | 8    | 6.07| 8.14| 6.10| 0.00| 0.00| 6.14| 8.27| 6.11| 0.00| 0.00|
| 11th (5) day  | 9    | 6.52| 8.75| 6.56| 0.00| 0.00| 6.62| 8.97| 6.58| 0.00| 0.00|
| 14th (1) day  | 10   | 5.92| 7.96| 5.97| 0.00| 0.00| 5.98| 8.11| 6.00| 0.00| 0.00|
| 14th (2) day  | 11   | 5.51| 7.40| 5.54| 0.00| 0.00| 5.57| 7.48| 5.54| 0.00| 0.00|
| 14th (3) day  | 12   | 9.53| 12.74| 9.58| 0.00| 0.00| 9.75| 13.09| 9.70| 0.00| 0.00|
| 15th (1) day  | 13   | 5.41| 7.27| 5.44| 0.00| 0.00| 5.46| 7.35| 5.43| 0.00| 0.00|
| 15th (2) day  | 14   | 5.26| 7.17| 5.44| 0.00| 0.00| 5.48| 7.53| 5.80| 0.00| 0.00|
| 15th (3) day  | 15   | 4.66| 6.27| 4.68| 0.00| 0.00| 6.68| 8.95| 6.64| 0.00| 0.00|

6.2. Experimental results of deflections (mm)

Table 3. Experimental results of deflections in each of the points.

| Day, t1st slab | Step | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 4th (1) day   | 1    | 0.09| 0.14| 0.11| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 4th (2) day   | 2    | 0.30| 0.48| 0.27| 0.00| 0.00| 0   | 0   | 0   | 0.00| 0.00|
| 7th (1) day   | 3    | 0.53| 1.01| 0.65| 0.00| 0.00| 0.36| 0.55| 0.20| 0.00| 0.00|
| 7th (2) day   | 4    | 0.99| 1.66| 1.06| 0.00| 0.00| 0.69| 1.06| 0.65| 0.00| 0.00|
| 11th (1) day  | 5    | 1.09| 1.94| 1.29| 0.00| 0.00| 0.79| 1.36| 0.88| 0.00| 0.00|
| 11th (2) day  | 6    | 1.25| 2.06| 1.38| 0.00| 0.00| 1.07| 1.82| 1.17| 0.00| 0.00|
| 11th (3) day  | 7    | 1.83| 2.44| 1.45| 0.00| 0.00| 1.35| 2.47| 1.84| 0.00| 0.00|
| 11th (4) day  | 8    | 2.51| 3.81| 2.75| 0.00| 0.00| 2.22| 3.60| 2.34| 0.00| 0.00|
| 11th (5) day  | 9    | 3.01| 4.46| 3.17| 0.00| 0.00| 2.71| 4.29| 2.95| 0.00| 0.00|
| 14th (1) day  | 10   | 4.17| 6.22| 4.54| 0.00| 0.00| 3.96| 5.84| 4.28| 0.00| 0.00|
| 14th (2) day  | 11   | 4.09| 6.14| 4.31| 0.00| 0.00| 3.71| 5.56| 3.98| 0.00| 0.00|
| 14th (3) day  | 12   | 8.93| 12.42| 9.08| 0.00| 0.00| 9.07| 12.32| 8.97| 0.00| 0.00|
| 15th (1) day  | 13   | 6.81| 9.90| 7.07| 0.00| 0.00| 6.37| 8.70| 6.27| 0.00| 0.00|
| 15th (2) day  | 14   | 6.74| 9.85| 7.06| 0.00| 0.00| 6.45| 8.86| 6.43| 0.00| 0.00|
| 15th (3) day  | 15   | 6.64| 9.67| 6.88| 0.00| 0.00| 6.65| 9.12| 6.58| 0.00| 0.00|

6.3. Cracking in the slabs:

Table 4. Experimental results of cracks in the slabs (mm).

| Period     | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| until Step 11 | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00|
| after Step 12 | 0.00| 0.10| 0.95| 0.80| 0.00| 0.05| 0.00| 0.00| 0.40| 0.25|
6.4. Graphics of the deflections in combination of points:

**Figure 5.** Deflections in point 1, 2 and 3.

**Figure 6.** Deflections in point 2.

**Figure 7.** Deflections in point 1 and 3.

**Figure 8.** Deflections in point 7.

**Figure 9.** Deflections in point 6 and 8.

**Figure 10.** Deflections in point 2 and 7.
6.5. Dependencies between the deflections in the areas of the shores and those in the middle of the slab from the experimental measurements of the first and second slabs

- In stage 2 and stage 4 in Figure 5, there is a gradual increase in the deflections of point 2 from those in points 1 and 3. This means that the eccentrically placed shores of the second slab relative to the first plate affect more deflections between the two propping shores of the first slab.
- In stage 4 and stage 6 in Figure 5, continuing deflections of the slab are reported despite the lack of load change in the stages. It is more clearly expressed in stage 6, due to the higher load and complete striking of the first slab.

6.6. Dependencies between elastic and experimental deflections in the first and second slab

- From stage 1 to stage 5 of Figure 6, the elastic deflections have higher values. This is due to the non-reporting of the mechanism for adjusting the height of the shores in the model. This is the reason for their increased stiffness in the model.
- In stage 6 of Figure 6, where the first plate is completely struck, the elastic deflections have values twice as high. This is due to the modeling of node 5 and 6 as simple joint without bending moment in the node. In real construction, these nodes are not simple joints. The most unfavourable case for the maximum value of the positive moment in the middle of the main field is accepted in the modeling.
- In stage 2 of Figure 8 and Figure 10, deflections in points 6, 7 and 8 of the formwork system are observed for the construction of a second slab, without any concrete still being laid in the formwork form. This is due to the deflections from the first slab on which the formwork for the second slab steps. The deformations in the first slab are obtained as a result of the load of the formwork system for the next level.
- In stage 4 of Figure 10, the graph of point 7 of the second slab is parallel to the graph of point 2 of the second slab, since the second slab is still fully cast and takes on with slightly smaller values, the deformation curve of the first slab.
- From stage 6 to step 7 of Figure 9, the elastic deflections in point 7 are higher due to the fact that again nodes 5, 6, 9 and 10 are modeled as simple joints. In real construction, these nodes are not pure simple joints.
- All these observations are confirmed in Figure 7 and Figure 9, where the comparisons of the elastic and experimentally measured values of the deflections have the same character.

6.7. Dependencies between elastic and experimental deflections in the two slabs in point 2 and 7

- From stage 1 to stage 8 of Figure 10, the relatively parallel movement of the two curves of the graph is visible regardless of the stage of striking and loading of the slabs. This is because the weight is distributed between the two slabs by the shores between them.
- In the middle of stage 9, after the complete striking of the two slabs, a violation of the parallelism of the two curves is observed, because, after the complete striking of the second slab, no more weight is transferred from the shores to the first slab. Each slab begins to work independently.

6.8. Features of the formation of cracks in the slabs

- In stage 6 of Figure 6, after calculation in the numerical model, we should get cracks in the middle of the first slab of the order of 0.24 mm. However, in the real construction cracks do not appear. This could again be due to some inaccuracies in the numerical model in nodes 4 and 5, because again in real conditions the node has more stiffness than that in the model. Thus, the bending moment in the middle of the slab is less than expected with the introduced static scheme in the model.
- In stage 8 of Figure 6 and Figure 9, after calculation in the numerical model, we should get cracks in the middle of the field of the first and second slab of the order of 0.62 mm and 0.28 mm, respectively. However, in the real construction, we get cracks of 0.10 mm and 0.05 mm. The
difference in the case is that we get serious cracks in nodes 4 and unit 5, respectively 0.95mm and 0.80 mm. In nodes on 9 and 10, we get cracks of 0.45mm and 0.25mm. With the adopted static scheme, we should not have any negative bending moment and cracks in these areas of the slabs. This again clearly shows the appearance of a negative bending moment at slab-column joints.

- During the assessment of cracks, especially at the stage of preparation, at lower strength and deformation characteristics of concrete, it is important to monitor not only the widths but also the crack depths. The non-destructive ultrasonic method is successfully used for this purpose. It should also be borne in mind that in such (unfinished) structures exposed directly to atmospheric conditions, there may be some limitations in the use of the ultrasonic method. Some details as well as experimental data on the subject are given in [12].

6.9. Features regarding the strength characteristics of the two slabs

- We observe a relatively low elastic modulus of concrete. In comparison, the first slab has a cubic compressive strength obtained on day 28 equal to 22.0MPa, and the value of the elastic modulus is 21.8GPa. Data on the development of concrete in the current experimental design are given in [13]. Similar results, typical for the building practice in the region, are also presented in [14] and [15]. This is probably due to the aggregate used for coarse aggregate in the ready-mixed concrete.

7. Conclusions

From the analysis of the results in the study, we come to the following conclusions and recommendations:

- The slabs of the experimental construction work together as the transfer of the loads from the first to the second slab flows through the shores in each of the stages. It follows that each slab to be produced by the Early striking method must be checked for coverage of the bending moments and the shear forces obtained from its self-weight and from the weight of next or more slabs above it, as well as the temporary loads that are likely to occur during construction.
- When inspecting the slabs for unregulated deflections, the fact must be taken into account that each slab propped by shores takes to a large extent the deformations of the slab below it.
- The deformations in the shores directly affect the deformations in the slabs. The more detailed the models of the shores, the more accurate the results will be obtained from the slab checks using the numerical model results will be. Failure to take into account the height adjustment device of the telescopic support in the model would make the shore model a stiffer element in the model than it is. It is also desirable to avoid eccentric arrangement of the telescopic supports supporting the slabs on the floors of the building.
- When performing inspections of flat slabs before applying the Early Striking method, when modeling a column-slab node as a simple joint, it should be borne in mind that the obtained bending moments are in favor of safety in terms of positive moments, but not in favor of safety regarding the negative moments of the end and middle supports of the slab. In addition to checking for cracking and irregular deflection in the main field, an important point is to check in the negative moment areas above the columns (especially the end ones, where the negative moment is usually considered zero). At the discretion of the designer, the node can be modeled as stiffer and attention paid to the values of the negative moment in it at different stages of the checks for striking and loading the slab. This is recommended because in case of possible loading from a higher slab (using shores), placing heavy temporary loads on one of the plates and insufficient reinforcement in the upper zone of the plate at the node (obtained from the calculations at the initially accepted simple joint connection of the node), the cross-section of the slab in the upper zone of the slab and near the column can be compromised by unwanted cracks.
- It is recommended that before starting the construction of buildings, research be done on what elastic modulus the concrete, which will be used for the construction of the structure has.
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