Evaluation of the deflected mode of the monolithic span pieces and preassembled slabs combined action

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Abstract. In single-story industrial buildings, the cost of roof covering comprises 40-55% of the total cost of the buildings. Therefore, research, development and application of new structural forms of reinforced concrete rafter structures, that allow to reduce material consumption and reduce the sub-assembly weight of structures, are the main tasks in the field of improving the existing generic solutions. The article suggests a method for estimating the relieving effect in the rafter structure as the result of combined deformation of the roof slabs with the end arrises. Calculated and experimental method for determining the stress and strain state of the rafter structure upper belt and the roof slabs with regard to their rigid connection has been proposed. A model of a highly effective roof structure providing a significant reduction in the construction height of the roofing and the cubic content of the building at the same time allowing to include the end arrises and a part of the slabs shelves with the help of the monolithic concrete has been proposed. The proposed prefabricated monolithic concrete rafter structure and its rigid connection with ribbed slabs allows to reduce the consumption of the prestressed slabs reinforcement by 50%.

1. Introduction

Single-storey framed type industrial buildings are built for many branches of industry. They are often equipped with bridge or overhead cranes, they have a long length and can be single-span or multi-span. Typical spans for reinforced concrete buildings are 12, 18, 24, 30m; the step of the column in the longitudinal direction is 6 or 12, in some cases 18 m. The space-planning concept of such buildings has to ensure free arrangement of technological equipment, freedom of movement and operation of overhead cranes, the possibility of upgradability or technical re-equipment [1]. It is important that the planning concepts of such buildings are optimal and provide strength, rigidity and stability for all loads and impacts, avoiding unnecessary costs.

Existing designs have certain drawbacks. In particular, farms have a large height; in 24 m spans the height of the roofing in the middle is 3.75 m. Slabs and span pieces have an articulated connection. Such a connection does not ensure the compatibility of these structures: the slabs are not involved in the work of the span piece, but serve only as a load. The slabs work according to the beam system - as one-span beams with hinged bearing at the ends. A large bending moment arises in them in the middle of the span. The slab longitudinal principal reinforcement is selected according to its size and, since the reinforcement is prestressed, the reinforcement lengthways cross-section does not change. It turns out that the reinforcement is used entirely only in the middle part of the span - in the zone of the ultimate moments, and the slab comes out to be overreinforced beyond the zone [2].
2. Research Methodology
Relative deformations have been determined by the tensometric method using the "multi-channel measuring complex TDS530". Measurement of rotation angles, horizontal and vertical displacements has been performed using the "6-PAO" flexometer. Automated processing of the results has been carried out using the Microsoft Office Excel software package. Theoretical Calculations of the rafter structure elements and the roof slab have been carried out in accordance with CD 63.13330.2012 and CD 20.13330.2011. Numerical calculations have been carried out using the "SCAD Office 11.5" licensed software package. The degree of the results reliability has been estimated with the help of modern mathematical handling method of experiments and has been determined by the acceptable convergence of the results of the calculations and experimental measurements. Conventional methods, certified equipment and instruments [3] have been used for the implementation of the experiments. Results of the investigation are reproducible under multiple measurements. Design data have been based on the basic theories of reinforced concrete and do not contradict them. An additional point is that the results have been examined by comparison with solutions of similar problems published in Russian and foreign sources.

3. The results
The design model of the space structure in the form of a continuous two-component compound beam has been accepted, where the rafter structure serves as the lower belt and the upper one serves as a beam equivalent to the slabs. For the convenience of calculation the span piece with two cantilevers, the latter are replaced by the upper belt of total rigidity, and the load coming from the cantilevers is summed and applied to the belts along the axis of the compound beam. The internal static irresistibility of the two-component compound beam with continuum links is revealed by the force method for which it is divided into two rods along the joint, and linear vertical Vx and tangential tx reactions are applied in the cross section.

The resulting shearing forces in the shear bonds in the zone of monolithic concrete perceive both the seam concrete and the reinforcement output of the slabs longitudinal edges crossing the contact zone. In the contact joint shear forces are perceived both by means of the concrete resistance of the contact zone to the displacement Q_ (b, sh), as well as by means of the work of the reinforcing outputs Q_ (s, tot) at the stage of the concrete operation before the cracks formation. After the formation and the cracks opening in the contact seam, the shear forces continue to be perceived by the reinforcement output crossing the contact zone, and also by means of the cohesion forces Q_sn along the longitudinal crack edge.

For the experimental investigations of the slabs combined action with the upper belt of the rafter structure, two models have been made, each of them consisting of a reinforced concrete beam of the T-section serving as a span piece; the supporting walls have been rigidly attached to the beam with a step of 1500 mm and 4 slabs resting on the walls of the span piece and have been mounted by welding the embedded metal items at two points. The rigid connection of the slabs to the walls and to each other is ensured by the forces of the monolithic concrete adhesion and the reinforcement outputs called for the span piece and the ribbed slabs [4].
The dimensions of the ribbed slab model are 1600х1490 mm. The length of the bearing part of the slab model is 500 mm, in the span it comprises 1100 mm and in the height it is 225 mm. The form of the model slab is made of plywood grade "OSB" of 9 mm in thickness and wooden beams 50x50 mm in thickness.

The elements of the slab model and the upper belt of the span piece have been assembled separately. After the removal of the formwork all the separate elements of one model have been assembled in such a way as to form a rigid knot connecting the slabs with the upper belt of the span piece and the corresponding real knot of the slabs bearing on the rafter structure with a scale of 1: 2.

To register the relative deformations of the monolithic part of the span piece, the end arris and the part of the slab shelf, 3 rows of tensoresistors having 15 pieces in line (3 on the span piece and 12 on the slab) have been glued to the slab surface and the span piece (Figure 2).

The slabs loading with the span piece has been carried out by means of a hydraulic pump station, transferring the load from the hydraulic cylinder to the slabs through a metal installation [5].
The deflection growth is limited at the middle of the span piece under the external forces of 130 kN. The histogram characterizing the rotation angles of the end and the middle longitudinal slabs edges is shown in Figure 3.
Figure 3. Histogram characterizing the rotation angles of the longitudinal slabs arrises: F1 – the angle of rotation of the middle arris; F2 – the angle of rotation of the end arris.

Figure 3 shows that the angular deformations of the end longitudinal slabs arrises are greater before reaching the maximum deflection of the span piece then in the middle arrises: by 50% when loading 40 kN; by 3.5% when loading 120 kN.

When the maximum deflection of the span piece is reached, the angular deformations of the middle arrises are greater than in the end arrises: by 4.8% with a load of 140 kN; by 27% when loading 220 kN. This shows the dependence of the angular deformations of the longitudinal slabs arrises on the deformations of the span piece and that the end longitudinal slabs arrises work under the most severe conditions and the maximum forces reach their maximum values at the points of their connection with the span piece [6].

The bending moment in the span piece cross section passing through the tensoresistor (T23) with an absolute deformation of $\Delta x = 204.10^{-6}$ under the load of 130 kN and the maximum deflection of 7.9 mm has been determined. The magnitude of the bending moment in the designed section of the span piece with account of the interworking with the slabs, is 65.57% lower than in the span piece without taking into account the combined action (Figure 4).

Figure 4. Diagrams of the span piece bending moments: 1) without considering the interworking with the slabs; 2) taking into account the interworking with the slabs.

The system failure took place at the sloping section under the action of the transverse forces in the longitudinal end closer to the bearing under the breaking load of 230 kN.

The results of the investigation of the relative linear deformations have been presented in Table 1 and in Figure 5 upon tensoresistor readings (T1-T15).
Table 1. Relative deformations (μm / m) upon tesoressistor readings

| load (kN) | T1   | T2   | T3   | T4   | T5   | T6   | T7   | T8   | T9   | T10  | T11  | T12  | T13  | T14  | T15  |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Δ10       | -3   | -3   | -4   | -5   | -2   | -1   | -1   | -9   | -3   | -5   | -4   | -4   | -3   | -4   | -2   |
| Δ20       | -5   | -5   | -5   | -5   | -2   | -2   | -1   | -8   | -1   | -1   | -1   | -7   | -6   | -3   | -7   |
| Δ30       | -7   | -8   | -15  | -15  | -1   | -12  | -4   | -33  | -12  | -23  | -17  | -16  | -11  | -10  | -6   |
| Δ40       | -8   | -10  | -15  | -15  | -12  | -6   | -46  | -14  | -29  | -23  | -21  | -14  | -13  | -7   | -7   |
| Δ50       | -12  | -15  | -28  | -30  | -26  | -32  | -14  | -68  | -18  | -42  | -33  | -30  | -21  | -20  | -11  |
| Δ60       | -16  | -20  | -37  | -41  | -37  | -45  | -21  | -95  | -22  | -54  | -41  | -38  | -28  | -24  | -16  |
| Δ70       | -19  | -24  | -45  | -48  | -45  | -56  | -27  | -117 | -25  | -63  | -49  | -46  | -34  | -30  | -18  |
| Δ80       | -22  | -29  | -53  | -57  | -54  | -67  | -33  | -139 | -29  | -74  | -57  | -52  | -39  | -34  | -20  |
| Δ90       | -24  | -31  | -59  | -64  | -61  | -79  | -38  | -158 | -32  | -82  | -64  | -59  | -42  | -38  | -21  |
| Δ100      | -24  | -32  | -64  | -69  | -67  | -86  | -42  | -170 | -33  | -89  | -68  | -63  | -46  | -39  | -21  |
| Δ110      | -24  | -33  | -67  | -74  | -72  | -94  | -47  | -180 | -35  | -96  | -73  | -66  | -47  | -39  | -21  |
| Δ120      | -23  | -34  | -68  | -78  | -77  | -100 | -50  | -190 | -35  | -78  | -68  | -49  | -39  | -20  | -19  |

Reliability of prefabricated slabs mating with prefabricated monolithic span piece has been proved by the results of the experimental investigations.

According to the tesoressistor readings a linear dependence of the slabs deformations on the span piece deformations has been established, which is explained by the compatibility of the slabs with the span piece and is also proved by the increase of the upper shelf calculated width of the double-T span piece cross section by a 75% that leads to the increase of its bearing capacity.
4. Discussion
Comparison of the numerical investigations results with the experimental data have showed their satisfactory convergence. The results of the experimental investigations for determining the forces in the slab model taking into account the influence of the span piece differ from the results of the theoretical calculations by 1.53%. The calculated deformed model scheme in the computational estimation has coincided with that obtained in the experiment. Linear dependence of the deformation of the end arris and a part of the slab shelf from the deformations of the span piece has been determined basing on the results of the investigations. In the case of the span piece free deformation, the maximum absolute value of the vertical displacement was 6.8 mm with a load of 150 kN according to the computational estimation of the SCAD office complex. In the case of joint deformation of slabs with the span piece, the maximum vertical displacement of the span piece was 4.5 mm with a load of 150 kN according to the results of the experimental investigations. In numerical calculation, the slabs and the span piece combined action is maximal in the zone of their junction, which corresponds to the results of the experiment and makes it possible to include the test zone in the work of the span piece [7].

5. Conclusions
1. The proposed cast-in-place and precast rafter structure allows to reduce the consumption of prestressed slab reinforcement by 50% in comparison with the typical solutions of the disc coating. This reduces the height and the weight of the assembled part of the rafter structure, which reduces the labour intensivity of its transportation and installation.
2. It has been found that the bending moment in the calculated section of the span piece is 65.57% lower with allowance for the interaction with the slabs, than in the span piece without taking into account the combined action.
3. Linear dependence of the deformations of the end slabs arris on deformations of the span piece has been established. Under different loads, the rate of the longitudinal deformations of the end slabs arris is 40-50% smaller than the longitudinal deformations of the span piece.
4. When calculating the strength of the upper belt of the proposed rafter structure, it is necessary to include the end slabs arris and part of the shelf in its work by increasing the width of the upper shelf by 75%.

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