Numerical Comparison of HPFRC and HPC Ribbed Slabs

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Abstract. The problem of limited resources is actual nowadays. One of the ways for solving this problem can be the use of high-performance fiber reinforced concrete as a structural material for elements subjected to the flexure. The dispersive reinforcement improves the properties of the concrete and allows reducing the required dimensions of cross-section and ratio of longitudinal reinforcement for members subjected to flexure. This research includes the numerical comparison of ultimate limit state and serviceability limit state of ribbed slabs from high-performance concrete (HPC) and high-performance fiber reinforced concrete (HPFRC) behavior, considering the different deformative properties of these materials. The effective use of these materials has been studied using a nonlinear finite element model. This model is created by using a beam type element with a multilayer cross-section, where each layer has a non-linear stress-strain relationship, according to the layer materials such as HPC, HPFRC, or steel bars. The finite element model used for the limited plates is validated. Results of experiment showed, that used calculation model describes with sufficient accuracy the behaviour of the ribbed slabs. The difference between design and experimentally determined breaking load is less than 6% for ribbed slab. The use of HPFRC for ribbed slabs with the spans from 6 to 12 m is justified so as using of HPFRC instead of HPC enables to increase 42-46% the intensity uniformly distributed load for the ribbed slabs with the same cross-sections and allowed deflections.

1. Introduction
As the amount of people in the world is growing, the problem of availability of non-renewable resources is actual. It is important to use resources efficiently. High-performance concrete (HPC) allows to design thin-walled load-bearing structures, thus reducing the self-weighing of structure and saving resources.

High-performance concrete is brittleness material, which is dangerous characteristic for construction material. The use of fibers insignificantly affects the strength of the concrete peak, but it reduces the fragility of high-performance concrete and significantly improve the deformative properties of the concrete in post-peak stage by fiber bridging effect [1-6].

Probably, cross-section dimensions and amount of additional longitudinal reinforcement for elements subjected to the flexure can be decreased by adding fibers in high-performance concrete composition. Thus, reducing cost of labor and delivery of additional longitudinal reinforcement. Thereby, the aim of this study is numerical comparison of behavior of high-performance fibre reinforced concrete (HPFRC) and HPC ribbed slabs to determine possibility of decreasing of slabs
cross-section and ratio of longitudinal reinforcement. The obtained results can be used for the initial design stage to select the used material.

2. Methods

2.1. Object of investigation
The elements subjected to the flexure are selected with the configuration of the ribbed slabs as it is shown in figure 1, with the longitudinal reinforcement bars embedded in the ribs of the slab. This configuration makes it possible to effectively integrate different solutions, such as communications and phase-change materials into the slab structure without increasing the overall height of the structure and maintaining the height of the story.

For comparison of behavior of HPC and HPFRC with steel fiber dosage 25-35 kg/m3, high strength concrete of C80/95 class [7] and high-strength steel of longitudinal reinforcement with yield strength of 1100 MPa are used. Used stress-strain curves of the HPC and HPFRC are shown in figure 2.

2.2. Design model
The developed numerical model of the slab allows appreciating the improvement of deformative properties of concrete from the use of fibers by defining the stress-strain curve of the respective
material. The developed non-linear design module based on the MATLAB has been used for creating slab calculation models. The structure is modelled by multi-layer beam-type finite elements, where for each of the layers is assigned its own non-linear stress-strain curve. This module allows designing a structure from HPC and HPFRC with an additional longitudinal reinforcement as it is shown in figure 3.

The non-linear behavior of HPC and HPFRC materials is characterized by degradation of modulus of elasticity cause of cracking by special damage parameter of the material [8]. The mechanical approach of continuous damage is used for each layer. The non-linear mathematical problem is addressed using the modified Newton-Raphson approach, where a stiffness matrix is recalculated in each load step.

3. Model validation
The developed numerical model which considered non-linear behavior of high-performance fiber reinforced concrete material is validated by the experimental data for free supported specimen of ribbed slab with span 1.23 m in tree-point bending (figure 4 a)). The geometric dimensions of the slab prototype cross-section are shown in figure 4 b). Each rib has B500 steel longitudinal bar with a diameter of 6 mm. The bars are located 10 mm from the outer edge. The protective layer of the left bar is 7 mm from the bottom and of the right bar - 11.5 mm.

Ribbed slab from high-performance synthetic macro fiber reinforced concrete is considered as object of study. Polypropylene (PP) Strux 90/40 fibers were used. The amount of fiber is 0.5% of the concrete volume. For 40 mm long fibers with an aspect ratio of 90, the tensile strength is 620 MPa, the modulus of elasticity - 9.5 GPa and the elongation - 10%.

Compressive strength of cube specimen with dimensions 10x10x10 cm from high-performance synthetic macro fibers reinforced concrete, according to compressed cube tests, is 92.5 MPa. Consequently, \( f_{cm} = 78 \text{ MPa} \) has been accepted for the compressive strength of the high-performance concrete, 41 GPa for the modulus of elasticity and 4.6 MPa for tensile strength.

A 10 x 10 x 10 cm cube (figure 5) has been modelled to determine the stress-strain curve of the high-performance synthetic macro fibers reinforced concrete, defining separately parameters of high-performance concrete and PP Strux 90/40. A model with 20 mm long fibers and twice the amount of fibers - 1612 fibers is selected because of the low stiffness of synthetic fibers at its addition time and, because fibers in the concrete structure do not retain their original straight shape.
Figure 5. Random placement of fibers (taking into account the effect of form walls) in the cube with 20 mm long 1612 polypropylene fibers.

Tensile stress-strain curve for high-performance PP Strux 90/40 fibers reinforced concrete obtained by the modelling of cube sample in tension is shown in figure 6.

Figure 6. Tensile stress-strain curve for high-performance PP Strux 90/40 fibers reinforced concrete.

Calculation criterion of the slab: is a 100-fold reduction of the modulus of elasticity, corresponding to the damage factor [8] $D = 1 - E/E_0 = 0.99$. The diagram of the slab specimen damage factor $(1 - E/E_0)$ in the three-point bending is shown in figure 7.

Figure 7. Scheme of the slab specimen damage in three-point bending.

The hydraulic loading device and the displacement measuring devices used in ribbed slab specimen three-point bend test were connected to the computer. Measurements from these devices were fixed
automatically by computer. Experimental load-displacement curve of ribbed slab specimen in three-point bending was obtained. Process of the laboratory testing is shown in figure 8.

![Figure 8. Laboratory testing of the ribbed slab specimen in three-point bending.](image)

Load-displacement curves of ribbed slab specimen in three-point loading, according to laboratory testing and numerical model calculations, are summarized in figure 9.

![Figure 9. Load-displacement curves for ribbed slab specimen.](image)

As a result of the non-linear calculation, by modelling the ribbed panel with the multi-layered final elements, the destructive load of the panel was 14.51 kN, at the moment when the experimental destructive load for the ribbed panel was 15.42 kN in the three-point bending test. Consequently, the created calculation model has shown a precision of more than 94% with regard to the destructive load.

4. Results and discussion

The maximum bending moment value in the middle of the ribbed slab shelf as a function from the thickness of the shelf for the high-performance concrete and high-performance fiber reinforced concrete and comparison of required shelf thickness at concentrated load F=20 kN in the middle of the shelf span is summarized in table 1.

| Material | Calculation equation for bending moment M | Required shelf thickness t (mm) |
|----------|------------------------------------------|-------------------------------|
| HSC      | M = 0.001 t^2 - 0.007 t + 0.0618          | 55                            |
| HPFRC    | M = 0.0013 t^2 + 0.0104 t - 0.3669        | 45                            |
The calculations show that the shelf of the ribbed slab from high-performance fiber reinforced concrete can take up a bending moment value of 38-41% higher than the shelf from the high-performance concrete with the same thickness. For example, taking into account the technological limitations of manufacturing and assuming a step of 5 mm of the thickness of the slab shelf, the thickness of the shelf, which will provide a load-bearing capacity of $F = 20$ kN at the slab width of 1 m, which causes about 2.5 kNm bending moment, is 45 mm for HPFRC, while for the HPC it is 55 mm, which is by 22% higher.

According to the obtained results from the calculations of the maximum moment in the middle of the free supported ribbed slabs with width equal to 1 m and uniformly distributed permanent load and imposed load with characteristic value 5 kN/m² for slabs with various heights and bars diameters of the ribs and spans 6, 8, 10 and 12 meters, differences, between the load bearing capacities of the slabs of HPC and HPFRC with additional longitudinal reinforcement, are small. The load bearing capacities of the HPFRC slabs are 5-10% higher than that of HPC slabs.

The calculations of the serviceability limit state are the determining factor for ribbed slabs as structures subjected to the flexure. The maximum bending of the slab in the middle of the span is determined by the slab self-weight and distributed imposed load. A 1/250 part of the slab span has been accepted as a maximum available value of the vertical displacements.

The curves for the HPC and HPFRC ribbed slabs with 4 different cross-sections, describing the value of distributed load $q$, at which vertical displacements in the middle of the slab span is equal with L/250 for slabs with span from 6 to 12 meters, is summarized in figure 10.

As it can be seen from figure 10, the slabs from high-performance fiber reinforced concrete can take up distributed load, which is 42-46% higher, than that load for the slabs made of high-performance concrete with the same cross-section parameters.

As a result, it can be concluded, that the use of HPFRC can reduce the material consumption of the high-performance concrete and longitudinal reinforcement. For example, comparison of the material consumption of ribbed slab with span 10 m, which needs cross-section of HPC H340-D22 or HPFRC H320-D16 (according to the figure 10) and taking into account that width of the rib of the slab is rounded up by 10 mm and is equal to sum of 3 diameters of longitudinal bar and 20 mm, is summarized in table 2.

![Figure 10. Uniformly distributed load, which satisfy the serviceability of the slabs on their spans for different slab height and reinforcement bars diameters for HPC and HPFRC. HPFRC – high-performance fiber reinforced concrete; HPC – high-performance concrete, H - slab height, D – bar diameter.](image-url)
Table 2. The comparison of material consumption of the 1 m wide ribbed slab with span 10 m.

| Material | Shelf thickness, mm | Width of the rib, mm | Slab height, mm | Diameter of bar, mm | Area of concrete, mm² | Area or bars, mm² | Δ, % | Area or bars, mm² | Δ, % |
|----------|---------------------|----------------------|-----------------|---------------------|----------------------|-------------------|------|-------------------|------|
| HSC      | 55                  | 90                   | 340             | 22                  | 106 300              | -                 | 760.27 | -                 |
| HPFRC    | 45                  | 70                   | 320             | 16                  | 83 500               | 21.4              | 402.12 | 47.1              |

5. Conclusions

Possibility to increase load-bearing capacity of the high-performance concrete ribbed slabs subjected to flexure by adding fibers was checked and confirmed by calculations. The use of high-performance fiber concrete as ribbed slab material is effective for slabs with span from 6 to 12 meters in comparison with high-performance concrete slabs with the same cross-sections. The shelf of HPFRC slab takes up a bending moment, which is 38 ... 41% higher than for the shelf of HPC slab. The HPFRC slab can take up 42 ... 46% higher distributed load than HPC slab with the same parameters of cross-section and allowed vertical displacement.

The difference in the ultimate load between the calculated with developed numerical model and experimental results is less than 6.0%. The specimen behavior of the numerical model is similar to the experimentally obtained of the slab, which leads to the conclusion that the developed constitutive model of material behavior with sufficient precision describes the behavior of the ribbed slab subjected to the flexure.

A performance analysis and cross-comparison of elements from HPC and HPFRC leads to the conclusion that the use of HPFRC for slabs with span 6-12 m allows reducing of the cross-section dimensions of the ribbed slab and the additional amount of longitudinal reinforcement more than 20%. Considering the reduction of materials to be used, the logical conclusion is that the costs of transporting and labor cost will also be reduced. In addition, dispersible reinforcement increases safety of the structure thanks to the beneficial effects of fibers on the plastic properties of concrete. The obtained results of calculations allow selecting of the used material and initial parameters of the slab cross-section for the first stage of design process.

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References

[1] Olivito R S and Zuccarello F A 2010 An experimental study on the tensile strength of steel fiber reinforced concrete Composites: Part B 41 246–255
[2] Singh H 2017 Steel fiber reinforced concrete - behavior, modelling and design (Ludhiana: Springer) p 172
[3] Song P S snd Hwang S 2004 Mechanical properties of high-strength steel fiber-reinforced concrete Construction and Building Materials 18 669–673
[4] Vougioukas E and Papadatou M 2017 A model for the prediction of the tensile strength of fibre-updated concrete members, before and after cracking Fibers 5(3) 27
[5] Kazemi M T, Golsorkhtabar H, Beygi M H A and Gholamitabar M 2017 Fracture properties of steel fiber reinforced high strength concrete work of fracture and size effect methods Construction and Building Materials 142 482–489
[6] Aydin S 2013 Effects of fiber strength on fracture characteristics of normal and high strength concrete Periodica Polytechnica Civil Engineering 57(2) 191–200
[7] EN 1992-1-1 “Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings”
[8] Sliseris J 2018 Numerical analysis of reinforced concrete structures with oriented steel fibers and re-pack *Engineering Fracture Mechanics* **194** 337–349.