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Experimental Study and Numerical Modelling for Flexural Capacity of FRC Structural Elements

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***Abstract* - Concrete reinforced by short steel fibres is typical brittle matrix composite, in which fibres are impeding cracks growth, such way increasing material's tensile strength. The use of steel fibre reinforced concrete (SFRC) in structures with high physical and mechanical characteristics makes possible to reduce their weight and cost, to simplify their production technology, to reduce or eliminate reinforcement labour, at the same time increasing reliability and durability. Randomly distributed discontinuous fibres are bridging the crack's flanks providing material's "ductility"- like non-linear behaviour at cracking stage. The current study is focused on one formulation of a specific type of concrete matrix with added fibres and without fibres. Concrete cubes and prisms without fibres and having in every situation the same content of 60 mm long fibres were fabricated. Cubes (100×100×100 mm) were tested in compression and beams (100×100×400 mm prisms) were tested under four-point bending (4PBT). Fracture process (crack growth) in the material was modelled, based on experimental results (part of experimental data was used). Finite element method (FEM) using the *ANSYS* program analysis were realized modelling stress distributions in the broken beams with the goal to predict fracture process. Model's prediction was validated.**

Keywords - short steel fibre, concrete, bending, numerical modelling.

I. INTRODUCTION

Main used material in the construction sector is a reinforced concrete. It is used twice as much as all other building materials altogether [1]. At the same time reinforced concrete is changing [2], [3], steel in the reinforcing rebars is replacing by various materials as well as, in many situations, rebars are replaced by short fibers added to the concrete mix [4]–[7].

Nowadays, one of the main engineering challenges is to develop and introduce in the mass production efficient reinforcement material. An example is: innovative reinforcing composite fibre metal-crystal-polymer with protective properties from the electromagnetic field [8], [9]. Short fibres may be the main or the secondary reinforcement (in combination with rebars) bearing the bending moments and the shear stresses. We can mention investigations were a concrete matrix is successfully reinforced with various fibres, made out of various materials [10]–[13] and by different methods [13]–[19]. Homogenously mixed concrete with added short fibres is used widely for shrinkage crack arrest in combination with additional reinforcement [20]. A the same time fibers are improving resistance to cracking of the concrete structures [21]. One of the more important property of the Steel Fibre Reinforced Concrete (SFRC), with homogeneously distributed in the volume fibers, is its superior resistance to cracking and crack propagation [22]–[25].

The current study focused on mechanical properties investigation of a specific type of concrete matrix with added short steel fibres (60 mm), comparing results with the concrete without fibres. Cubes and beams were fabricated and tested, material fracture process was observed and then modelled, based on experimental results obtained in cubes compression tests and beams 4PBT. Model's predictions were validated by experimental data. Finite element method (FEM) using the *ANSYS* program analysis were realized modelling stress distributions in the broken beams with the goal to predict fracture process.

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II. Materials and methods

A. Materials

Generally, concrete containing a hydraulic cement, water, fine and coarse aggregates and admixtures, such as fly ash, silica fume and nano-silica. When selecting raw materials to produce a concrete matrix, preference was given to locally available mineral materials and cement according to EN-206. The water to cement ratio was *W/C* = 0.3 and the amounts of ingredients were fixed and is tabulated in the table 1.

Table 1 Designed concrete mix composition and used components

Composition	Weight, kg/m^3
Portland cement CEM I 42.5N (*SCHWENK Latvia Ltd.*, Latvia)	490
Rubble 2/6 mm	650
Quartz Sand 0.4-1.2 mm (*Saulkalne*, Latvia)	417
Quartz Sand 0-1 mm (*Saulkalne*, Latvia)	277
Quartz Sand 0-0.4 mm (*Saulkalne*, Latvia)	92
Silica Fume, grade 920D (*Elkem*, Norway)	51
Fly Ash (*SCHWENK Ltd.*, Kozienice, Poland)	110
Tap water	202
Superplasticizer *"Sikament® 56"* (*Sika Baltic SIA*, Latvia)	10
Total	2300

Crimped steel fibres with shaped cross-section were used in this research. The figure 1. shows the geometry of steel fibre *Tabix+ 1/60*. Concentration of fibres in the concrete mix was 78 kg/m^3. The properties of the fibre were tabulated in the table below.

Table 2 Specification of the steel fibres by supplier's data

Fibre Type	Length L_f, mm	Diameter d_f, mm	Density, kg/m^3	Tensile strength, N/mm^2	Modulus of elasticity, N/mm^2
Tabix+ 1/60 (*ArcelorMittal*, Luxembourg)	60	1	7900	1500	210000

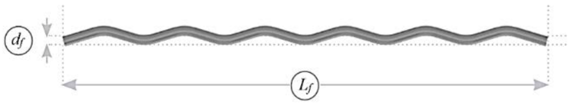

Fig. 1. Geometry of steel fibre Tabix+ 1/60, by supplier's data sheet.

B. Samples prepartion

Concrete mixing and casting details

The concrete mix with and without fibres was prepared for the study. The coarse aggregates, fine aggregates, cement, and silica fume were mixed first dry in a pan mixer. The superplasticizer was then mixed thoroughly with the water and added to the mixer. To obtain a fibre-reinforced concrete matrix, the fibres were dispersed by hand in the mixture to achieve a uniform distribution throughout the concrete. Fresh concrete mix was casted in steel moulds and compacted on a vibrating table.

Sample sizes

The samples were divided into Group A (5 beams without fibres) and Group B (5 beams with fibres). First, the concrete mix was casted into the prism's moulds of size 100×100×400 mm. The specimens were demoulded after 24 h and for maturing, were placed into a water tank until the time of testing. In the case of flexural tests, were used beam specimens (group A and B). Prisms were tested under bending till rupture and the averaged curves of these tests are reported in the load–deflection pictures (Fig. 7 and Fig. 8) and used for calculating the various parameters. After flexural strength tests were done, the non-cracked beam ends were cut into cubes of sizes 100×100×100 mm and then compressive strength tests were performed at 28 days from casting.

C. Expermental tests and results

Compressive testing procedure of concrete cubes

In the concrete design and quality control, concrete is classified by compressive strength. Many properties of a concrete, such as modulus of elasticity, tensile strength, permeability, etc., are believed to be dependent on the compressive strength and may therefore be deduced from the strength data. Though, the compressive strength cannot be utilised as a replacement for all properties, especially not for the increase of toughness observed in fibre-reinforced concrete. This means that for fibre-reinforced concrete some sort of toughness property is required, and that other test methods have to be utilized to characterise it [26]. Compressive Testing Procedure and strength of concrete cube the defining strength properties of these materials, be detected both by non-destructive methods [27]–[29] and by the classical destructive method in accordance with EN 12390-3. Standard compressive cube tests using 100×100×100 mm specimens were conducted to determine of the concrete compression strength including 14 specimen's data after 28 days.

A universal testing machine *Controls Automax 5* was used for testing the compressive strengths of cube specimens at 28th day from the casting moment. Load was applied in 0.25 kN steps for the period of 60s. The deflections were recorded with two *HBM WA20 LVDTs* sensors (*Spider8_1 CH 1* and *CH 2*) on to a computer connected through an electronic digital controller system.

Compressive strength of concrete cubes

Cubes in one formulation of a specific type of concrete matrix were tested. It was obtained that the compressive strength of the concrete cubes without fibres is 69.53 N/mm2 (concrete strength class C50/60 using correction factor 0.95 according to standard LVS 156-1 table 4). Compressive strength of the concrete cubes with steel fibres is 93.74 N/mm2 (concrete strength class C70/85 using correction factor 0.95 according to standard LVS 156-1 table 4). Using the test results stress (σ) and strain (ε) values were calculated and stress-strain curves were generated.

Four-point bending test (4PBT) procedure

4PBT were performed after 28 days from the casting moment. Used *Controls Automax 5* 4PBT testing machines a test with constant bending moment by the application of load through upper and lower rollers as shown figure 4 according to standard EN 12390-5. Load was applied until the specimens breaks completely. To obtain the deflection of the beam, the frame with two *HBM WA10 LVDTs* sensors on its sides used for recording deformations in prisms during the tests were placed at centre of the span. The maximum load was sustained, the deflections were recorded and the flexural strength was calculated.

Four-point bending test results

Group A and Group B were experimentally tested in flexure under four-point bending conditions observing their load carrying capacity in the macro cracking stage. The maximum force in SFRC strength analysis is the post-cracking behaviour up on high strain levels. According to the testing results, specimens of Group B reached the highest load carrying capacity as they had the concentration of fibres in the prisms. Specimens of Group A showed lower load carrying capacity comparing to the specimens with fibres. Experimental average curves are given in Fig. 7 and Fig. 8. Using the test results stress (σ) and strain (ε) values were calculated and stress-strain curves were generated (Fig. 2 and Fig. 3).

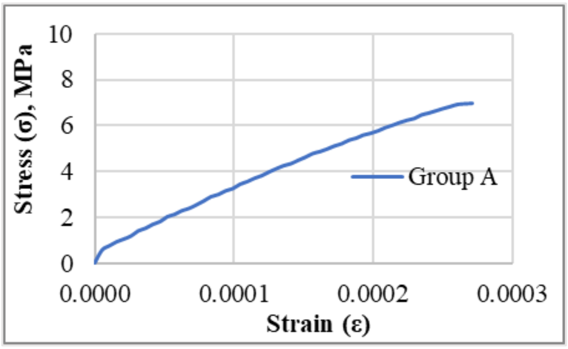

Fig. 2. 4PBT averaged experimental stress-strain curves of concrete for 28 days for Group A.

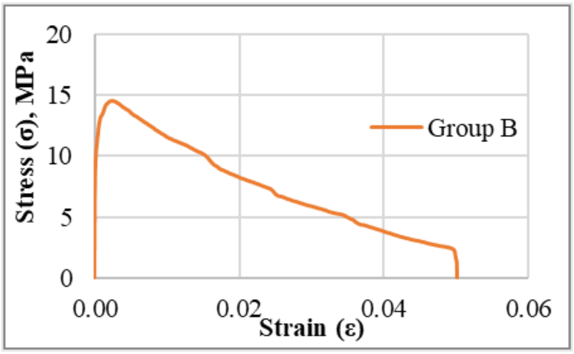

Fig. 3. 4PBT averaged experimental stress-strain curves of concrete for 28 days for Group B.

The presented results indicate that main contribution of steel fibres to a concrete. Fibers are working before and after matrix cracking. If a proper design is made, after the matrix cracking, randomly distributed, short fibres in the matrix arrests micro-cracks, bridge these cracks, undergo a pull-out process and are limiting cracks propagation [30], [31]. Steel fibres can increase significantly the bending and the shear resistance of concrete structural element. Specimens showed typical tri-linear variation in their load-deflection and load-crack mouth opening displacement curves under flexure.

D. Numerical modelling

Finite element (FE) analysis, allows to simulate the behaviour of reinforced concrete members with sufficient accuracy. A non-linear FE method is a numerical technique for obtaining approximate solutions to a wide variety of engineering problems. However, modelling of fibre-reinforced concrete is challenging as many parameters have to be taken into consideration to simulate the quasi brittle material behaviour of concrete accurately. [32]

In this study, FE modelling of beams with and without fibres is carried out using *ANSYS*, to simulate the behaviour of the control from linear through non-linear response and up to failure. One model of each group of samples were modelled in FEM software using *ANSYS*. A quarter of the full cube and beam was used for modelling by taking advantage of the symmetry of the sample, loading and boundary conditions (Fig. 5).

From the analyses the load deflection at mid span relationships until failure, and crack patterns that are obtained from numerical simulations were obtained and compared with the experimental results (Fig. 7 and Fig. 8). The load deflection plots obtained from numerical studies show good agreement with the experimental. The use of computer software to model these elements is much faster, and extremely cost-effective than make the real experiments.

SOLID65 element was used for modelling concrete material. The *SOLID65* element type available in *ANSYS* element library is a solid element with 8 nodes and has three translation degrees of freedom at each node. It can be used to model concrete with or without rebars and is capable of modelling cracking in tension, crushing in compression, plastic deformation and creep behaviour. *SOLID65* element requires linear isotropic and multilinear isotropic material properties to properly model concrete. [33]

Concrete material Elastic and Concrete material definitions were identified. In Elastic definition, the modulus of elasticity and *Poisson's* ratio were necessary. *Poisson's* ratio for concrete is assumed to be 0.2. The modulus of elasticity of concrete was determined by experiments. For Concrete definition, axial tension strength of concrete and shear transfer coefficients between crack surfaces for open and closed cracks were required. [33]

To facilitate the modelling process, it was assumed that the fibres in the element are divided into 3 equal parts in each of the 3 planes in the coordinate system. The volume ratio (0.01/3 = 0.00333) in each direction of the coordinate system was defined as the rebar volume divided by the total element volume. The orientation was defined by two angles (in degrees) from the element coordinate system. Material properties for the steel reinforcement for finite element modelling were taken as follows: E_s = 210 GPa and *Poisson's* ratio, v = 0.3. [34].

Fibres in the specimens are random distributed across the volume. Fibre-reinforced concrete is considered as a "quasy" homogeneous material. Called "homogeneous" doesn't mean homogeneous in reality, because during filling the construction formwork (mix flowing process) fibres added to concrete mix blend are obtaining non-homogeneous distribution and orientations in to fresh mix concrete volume which inevitably affects the mechanical properties of FRC [35]–[39]. Despite the fact that the fibres are mixed randomly, to facilitate modelling, it was assumed that the fibres were mixed homogeneously.

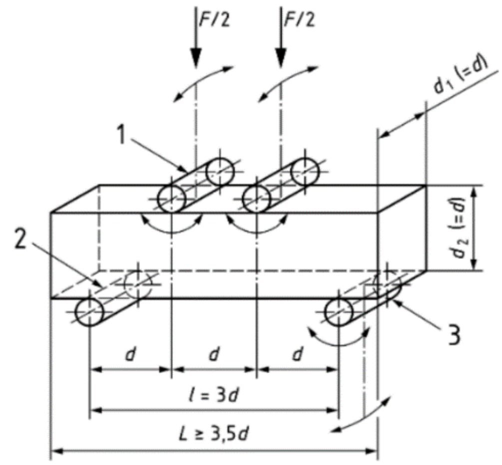

Fig. 4. Four-point bending test scheme (EN 12390-5) 1 – loading roller (capable of rotation and of being inclined); 2 – supporting roller; 3 – supporting roller (capable of rotation and of being inclined).

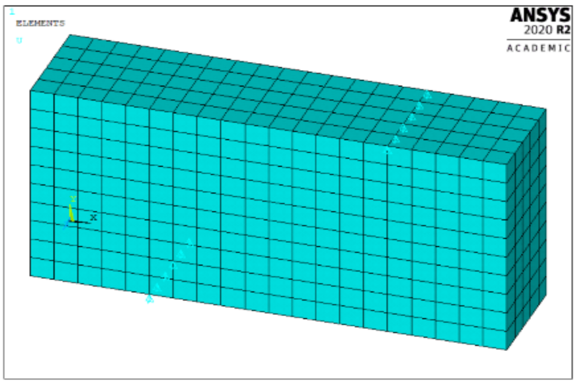

Fig. 5. Model of a quarter of the full beam in *ANSYS*.

Displacement in Y direction of the beam in *ANSYS* is shown in figure 6.

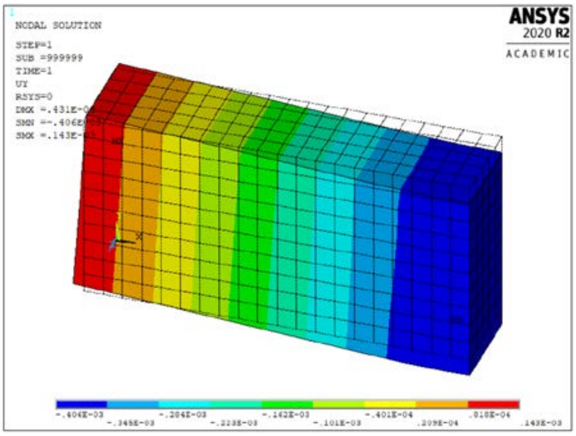

Fig. 6. Displacement in Y direction of the beam in ANSYS.

III. Results and Discussion

Averaged experimental load bearing curve comparison with numerical simulation results for prisms without fibres (Fig. 7) and with fibres (Fig. 8) were generated. The modelling results for Group A quit well approximate the data obtained experimentally, but to facilitate modelling the elastic properties of the concrete were not included, thereby a linear curve was obtained.

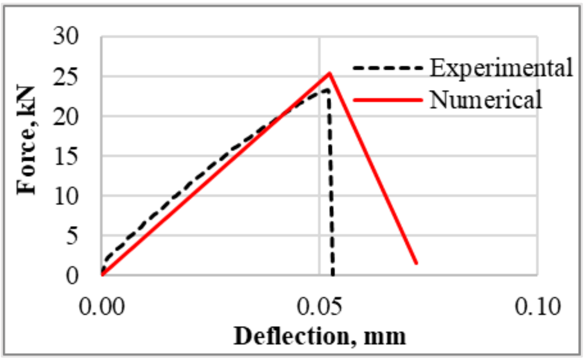

Fig. 7. Averaged experimental load bearing curve comparison with numerical simulation results for prisms without fibres (Group A).

Figure 8 shows that good agreement between experimental and modelling data is obtained: non-linear behaviour appears approximately at the load of 35 – 40 kN, and the load – bearing capacity of the prism is 49 kN. With the further loading, a drop of the force is observed in the experiments, since concrete due to cracking gradually goes out of loadbearing action, and the fibers take the load. Due to limitation of the applied FE model (the fibres in FE work only until the collapse of it), this phenomenon is not obtained numerically. By the same feature of the numerical model the drop of the force from 42 to 18 kN in the beginning of non-linear work of the prism could be explained.

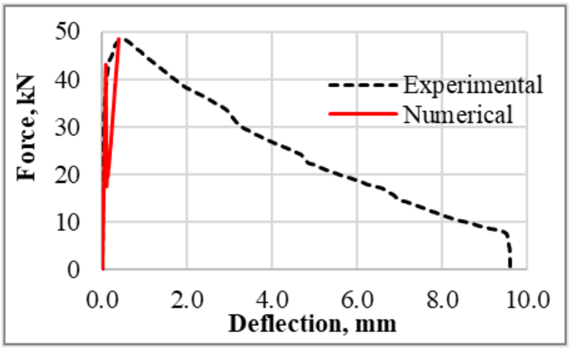

Fig. 8. Averaged experimental load bearing curve comparison with numerical simulation results for prisms with fibres (Group B).

IV. Conclusions

Modelling results agreement with experimental data is good in "general". The moderate disagreement in numerical values can have various reasons. Looking on data presented in Fig. 7 and Fig. 8 the possible reason for deviation from experimental data could also be because fibre orientation in the specimen contrary to modelling assumptions about random distribution across the volume and random distribution of orientation angles and the elastic properties of the concrete were not included in the model.

V. Acknowledgments

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