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MECHANICS
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LOAD BEARING CAPACITY OF STEEL FIBRES IN CONCRETE

TĒRAUDA ŠĶIEDRU IZRAUŠANAS SPĒKA NOTEIKŠANA FIBROBETONOS

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1. Introduction

While generally accepted design guidelines for steel fibre reinforced concrete (SFRC) are still unavailable, the use of such building material in structural elements is considerably limited regardless of its potential benefits. The design possibilities are further complicated by the fact that the two most widely used design recommendations in Europe developed by RILEM committee [1] and DAfStb [2] incorporate significant mutual differences thus raising uncertainty of design reliability. Therefore many investigations in the field have disassociated from the existing regulations and are focused on more fundamental understanding of SFRC behaviour. As an example, many attempts have been made to incorporate composite material mechanics and fracture mechanics to develop a fundamental method for material response prediction [3, 4].
The use of steel fibres in concrete instead of traditional reinforcement is beneficial mostly due to simpler casting procedure. Improvement of such material properties like toughness, wear and corrosion resistance can also be noted for SFRC when compared to traditionally reinforced

concrete structural elements. From point of view of mechanics, steel fibres serve the purpose of reinforcement by increasing the tensile strength and by improving post-cracking behaviour of concrete matrix which itself is a highly brittle material.

Technologically it is rather difficult to distribute a large content of steel fibres into the concrete mix because it negatively affects the workability. Furthermore, fibres are often a subject to an undesirable occurrence which is called fibre clustering. Clustering is more likely to occur when longer fibres are used in the mix. Therefore for the aim of good workability of the mix, steel fibres are limited both by their maximal content and length. These limitations have been fully taken into account for commercially available steel fibres. Recommended fibre dosage can usually be found on the fibre package.

Hence, from point of view of mechanics commercial SFRC can be considered as a short fibre composite. Logically, it corresponds to completely different post-cracking behaviour than traditionally reinforced concrete (with continuous steel bars) as the fibres in commercial SFRC are in most cases pulled out of the concrete matrix. This places the fibre pullout mechanism as a key factor to load bearing capacity and serviceability of SFRC structures.

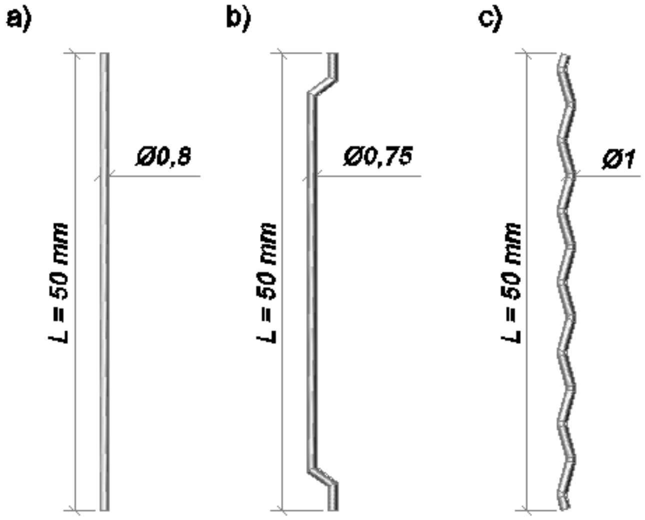


Figure1. Types of steel fibres: a) straight fibre; b) Dramix fibre; c) Tabix fibre

Following the previously stated, the present report is focused on investigating the pull-out process of commercially available fibres with the aim to determine the optimal type. Three types of steel fibres have been observed – straight fibres, fibres with end hooks (Dramix), and corrugated form fibres (Tabix) (see Figure 1).

2. Analytic approach

The analytic calculations were performed with the aim to determine internal stress distribution in SFRC that would illustrate the concept of fibre and matrix interaction in the system. Thus a model consisting of single fibre surrounded by concrete matrix was adapted from mechanics of composite materials. The simplest and most widely used model is the shear-lag model which was originally proposed by Cox in 1952. The model is centered on the transfer of tensile stress from matrix to fibre by means of interfacial shear stress. The principles of the shear-lag model are shown in Figure 2.

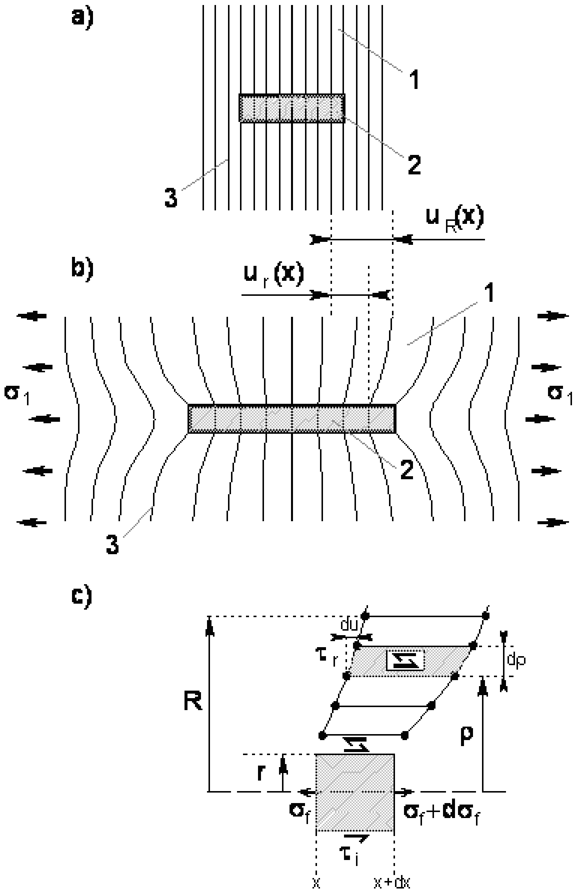


Figure 2. Shear-lag model:
a) unstressed system; b) displacements caused by tensile stress; c) shear stress variation (orig. figure from [5])

Reference lines are drawn on a fibre and the surrounding matrix, which are initially straight and normal to fibre axis. When subjected to external load the reference lines distort in the manner shown in Figure 2. Shear stresses in the matrix and at the fibre matrix interface are considered.

According to the model, equating the shear forces on neighbouring annuli of length dx gives:

$$2\pi r_1 \tau_1 dx = 2\pi r_2 \tau_2 dx \ . \qquad (1)$$

It follows that the shear stress τ in the matrix at any radius ρ is related to that at the fibre/matrix interface, τ_i by:

$$\tau = \tau_i (r/\rho) \ . \qquad (2)$$

In order to determine stress distribution between fibre and matrix, it is necessary to define their displacements. Fibre and matrix displacements themselves are unknown, but their differentials are related to identifiable strains – ε_f and ε_m respectively. For the fibre (Figure 2.) it can be assumed that:

$$du_r / dx = \varepsilon_f \ . \qquad (3)$$

For the matrix displacement we have to assume that the differential of u_R will approximate the far-field matrix strain ε_m which is close to the overall composite strain ε_1:

$$du_R / dx \approx \varepsilon_m \ . \qquad (4)$$

Following mathematic transformations as described in [1] stress distribution in the fibre can be determined as:

$$\frac{d^2\sigma_f}{dx^2} = \frac{n^2}{r^2}\left(\sigma_f - E_f \varepsilon_1\right), \qquad (5)$$

where $n = \left(\dfrac{E_m}{E_f (1 + v_m) \ln(R/r)} \right)^{1/2}$.

Equation (1.5.) is a standard second order linear differential equation from which fibre stress variation can be determined, according to specified boundary conditions [5].

3. Numeric approach

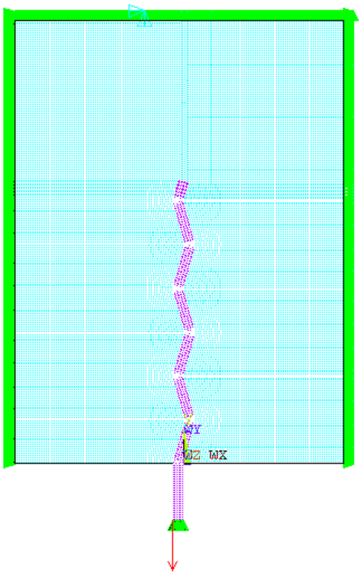


Figure 3. Finite element model for Tabix fibre

Numeric calculations in this study were performed also with the aim to determine internal stress distribution in fibre reinforced concrete. But unlike in analytic calculations described previously, in numerical calculations more complete depiction of stress distribution can be achieved.

All numerical calculations were performed in finite element program ANSYS 9.0 [6]. Finite element model for each case was built considering a single fibre embedded in the surrounding concrete matrix. Actual properties of fibre geometry and elasticity were entered although the model was two-dimensional. The constants for concrete were entered in the model after previously performed compression tests where modulus of elasticity was experimentally determined. At first geometrical size of concrete matrix was determined such that only the part that is affected by the presence of fibre was kept in the finite element model.

As depicted in Figure 3 very fine element mesh was generated.

In the finite element model concrete matrix represents only a limited fragment of discontinuous environment. Therefore the element nodes on the drawn borderlines were all assigned with coupled degrees of freedom. The pull-out load was applied parallel to fibre axis. Because only stress field distribution was of interest in the current study, the absolute value of the pullout load was not significant and unit load was applied in the model.

4. Experimental methods

In the experimental part of this research maximal pull-out load and fibre pull-out energy was determined for three types of commercially available steel fibres – straight fibres (marked F1), Dramix fibres (with end hooks) (F2) and Tabix fibres (corrugated) (F3) (Figure 1) Samples were prepared consisting of a single fibre symmetrically embedded in the concrete matrix (Figure 4). Concrete volume was divided in two parts during casting process by a plastic separator that prevents any of the tensile stress to be transferred across the concrete section. Thus all of the tensile stress was transferred only through the fibre that discontinuously crosses the separator (Figure 4).

Besides the investigation of three different fibre types, also three types of concrete matrices were observed. It was proposed that the concrete matrix that is reinforced by additional short steel fibres should have a higher resistance to micro-cracking thus enhancing the pull-out load and energy of longer steel fibre. Thus the types of matrices observed in the experimental study were: plain concrete matrix (marked B1), concrete matrix (of the same composition as B1) reinforced with 6 mm Ø 0,16mm fibres (content $25\,kg/m^3$) (marked B2) and also concrete matrix reinforced with a combination of 6 mm and 13 mm short fibres of the same diameter (total content $\approx 105\,kg/m^3$) (B3).

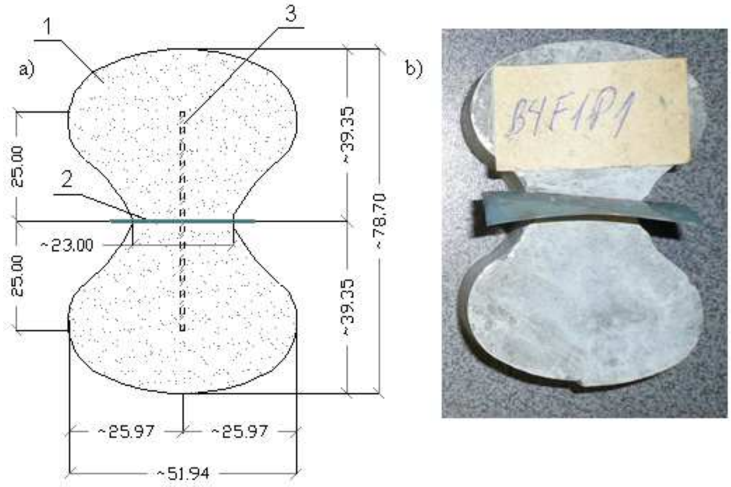


Figure 4. Formation of pullout test samples:1 – concrete matrix; 2 – plastic separator; 3 – embedded steel fibre

Overall 4 to 5 samples were prepared for each fibre/matrix combination. All samples were tested at the age of at least 28 days. The experiments were performed on high precision testing device "Zwick/Roell Z150". Pull-out load was measured by a load transducer (of capacity $1kN$) and the pull-out displacement by video extensometer "Messphysik".

5. Results

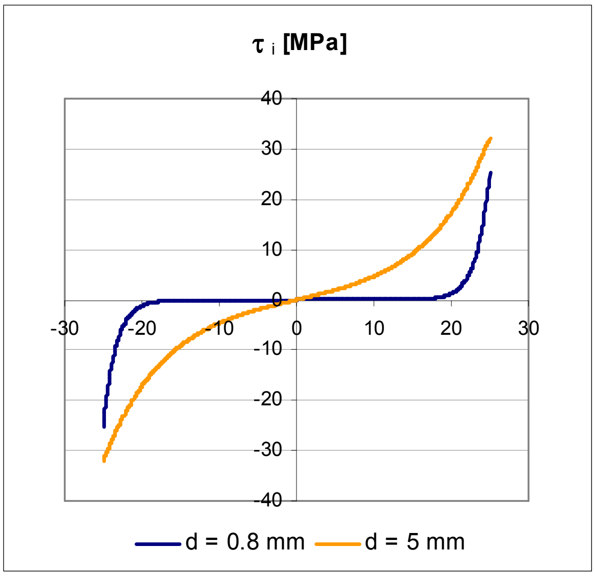


Figure 5. Shear stress distribution along straight fibre/matrix interface

Analytic results showed that stresses in the fibre reach the maximal value at fibre midpoint. At a particular fibre aspect (length vs. diameter) ratio the tensile stress in the fibre reach the peak value that corresponds to fibre strain equal to matrix and hence to the total composite strain.

On the contrary, shear stress at the fibre/matrix interface reaches the maximum value at fibre ends (see Figure 5). The interfacial shear stress distribution and concentration should be evaluated uppermost due to the fact that no chemical bond between fibre and matrix forms during hydratation reaction and in the hardened concrete only weak Van der Waals forces withstand interfacial sliding. Hence, this weak bond at the fibre/matrix interface is the main cause for initiation of fibre pull-out which can be considered as ineffective use of steel fibre yield strength potential.

Numeric results revealed the stress distribution in the initial stress state before initiation of interfacial sliding. As the observed material initially responds to loading elastically, the stress fields from the numeric results can be used to interpret the initiation of inelastic behaviour in the fibre/matrix system.

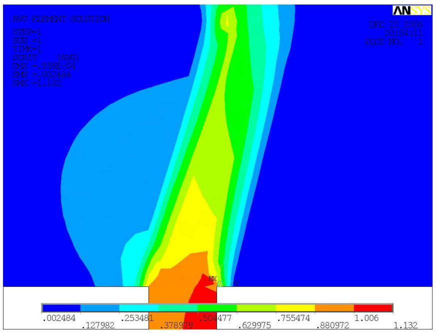


Figure 6. FEM modelling results for Tabix fibre

For example, stress fields depicted in Figure 6 which correspond to Tabix fibre at the entrance in the matrix show that in the initial stage the axial stress in the fibre is lower than applied stress. This means that in order to break, local straightening of the fibre has to occur at first. This is what should be observed in the experimental part of study.

The experimental results of fibre pull-out process of three different fibres are shown in Figure 7. As it is well noticeable in the figure, that on the contrary to straight fibres and Dramix fibres which were all pulled out from the concrete matrix, axial stress in Tabix fibres reaches the maximum yield value and the fibres break. This means that the potential of steel strength in this case is used effectively. In the case of straight fibres, experimentally determined maximal load at which fibres pull out was only 68,9(N) which is only 10 % of steel strength potential. For Dramix fibres determined maximal pull-out load was 284,4 (N) which is more than 3 times higher than for straight fibres. But also, in Dramix fibre pull-out process, only 50 – 60 % of steel strength was utilized.

As it can be seen in Fig.8 the pull-out load and displacement curves vary considerably, depending on the properties of surrounding concrete matrix. The matrix strengthening effect is clearly visible as the highest pull-out load corresponds to concrete matrix with highest content of additional short steel fibres. The strengthening effect was observed for both straight fibres and Dramix fibres (F1 and F2). For straight fibres the increase of pull-out load from 68,9(N) (for matrix B1) to 86,4(N) and 161,3(N) (for matrices B2 and B3 respectively) was observed (see Figure 8). In the same way values of the maximal pull-out load for Dramix (F2) fibres increased from 284,4 (N) (for matrix B1) to 308,1 (N) and 340,7 (N) (for matrices B2 and B3). For F3 (corrugated form) fibres the strengthening effect could not be observed due to fibre fracture prior to initiation of sliding. However, when the absorbed energy in the pull-out process was calculated (see Figure 9.), the additional resistance of short fibre reinforced matrix to fibre local straightening (prior to fracture) of F3 fibre could be detected. The pull-out energy characterizes the amount of work required for completely pulling the fibre out of the concrete matrix. It is known that after reaching maximal pull-out load, fibres resist the applied load by frictional forces on the fibre/matrix interface. Thus during the process of fibre sliding out of the matrix considerable amounts of energy can be absorbed. This is an aspect that also determines the quasi-plastic behaviour of SFRC structural elements.

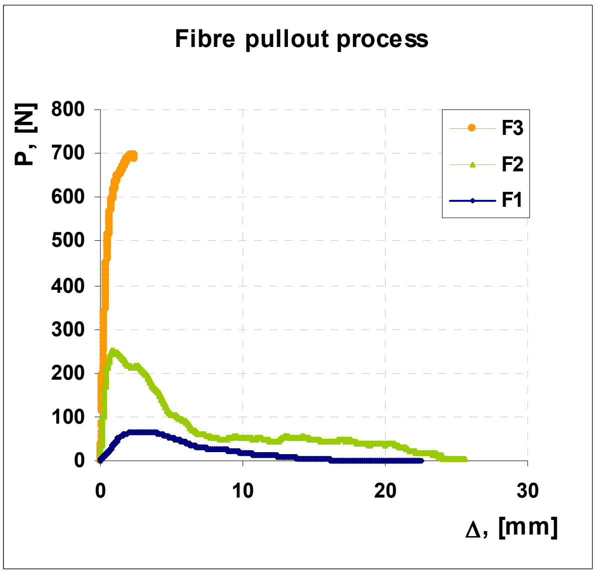


Figure 7. Experimentally determined pullout load-displacement relation for different fibres

In Figure 9 the total absorbed energy is divided into divisions that clearly mark out the differences in the pull-out behaviour of fibres and allow considering which parameters of fibres are most useful. For example, in Figure 9 it can be seen that there is a large amount of additional energy that is absorbed in the process of local fibre straightening (for F2 and F3 fibres). It can also be seen that the process of interfacial debonding requires more energy for corrugated shape fibres (F3). In general, the benefits of fibre profiling (F2 and F3) are clearly evident in comparison to straight fibres (F1).

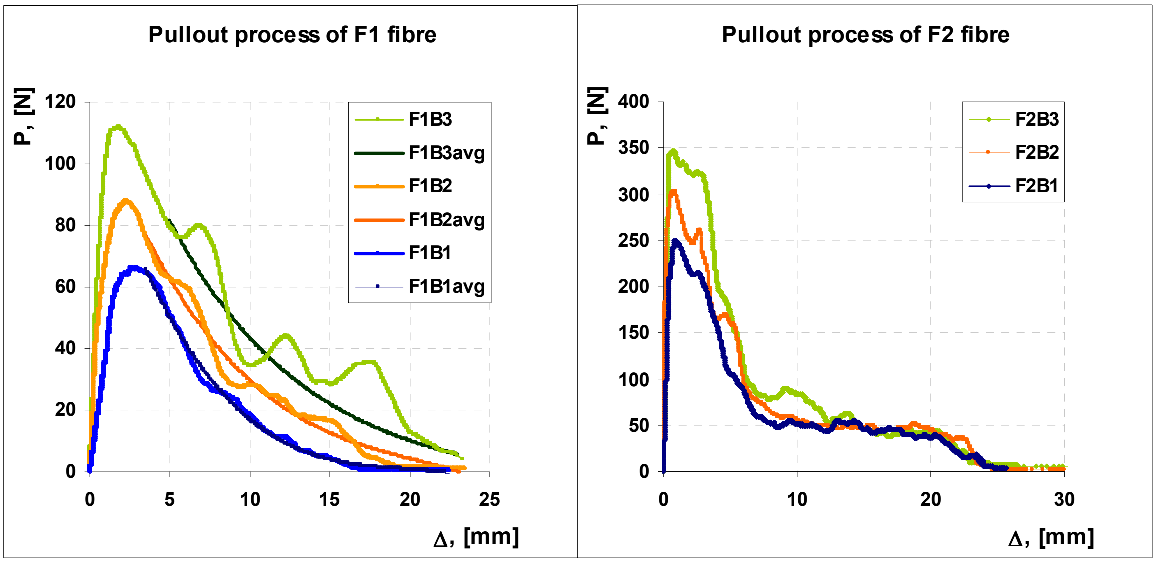
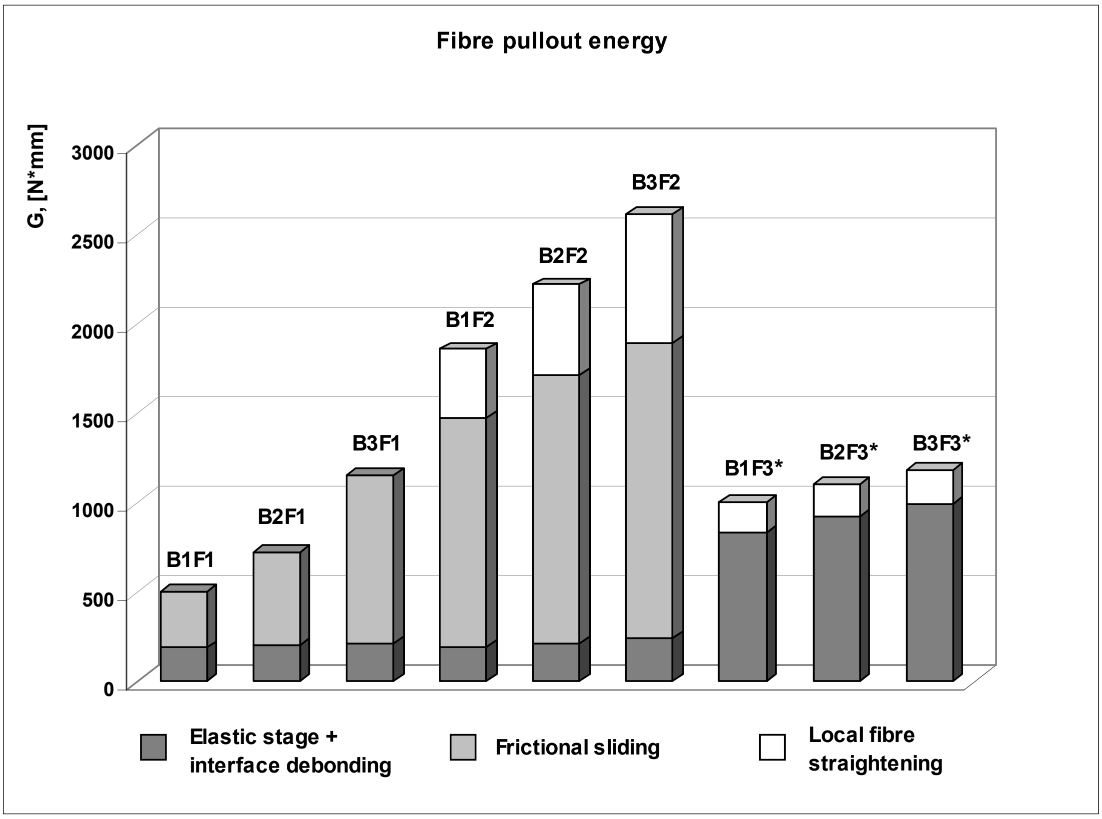


Figure 8. Pullout load- displacement curves for different fibre and matrix combinations



* Fracture of fibres

Figure 9. Pullout energy for different fibres in different stages

6. Conclusions

From the analysis of the obtained results following conclusions can be drawn:

1. Undulated form fibres Tabix 50/1,0 subjected to pullout load fully allow to use the potential of steel yield strength and can be considered as an effective reinforcement of concrete matrix. In comparison, in the pullout process of Dramix fibres (with end hooks) only 50 – 60 % of the steel tensile strength is put to use.
2. Reinforcing concrete matrix with short steel fibres is an effective way to increase pullout load and pullout energy of a longer steel fibre. Depending on fibre type the reinforced concrete matrix shows considerable resistance in all stages of longer fibre pullout.
3. The effect of short fibre reinforced matrix is more obvious in the case of straight fibre pullout when maximal pullout load increase of more than 2 times was reached. For Dramix fibre pullout most of the gain was observed in the stage after maximal pullout load as the reinforced concrete matrix offered greater resistance to local straightening and sliding of the fibre.
4. Numerical modelling of fibre pullout showed that the behaviour of undulated form fibre Tabix embedded in the concrete matrix is based on even stress accumulation whereas for straight fibres and Dramix fibres the most of stress is concentrated at fibre ends.

Acknowledgement

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Pupurs A., Krasņikovs A. Tērauda šķiedru izraušanas spēka noteikšana fibrobetonos
Rakstā tiek pētīta komerciāli pieejamo īso tērauda šķiedru mikromehāniska mijiedarbība ar betona matricu. Galvenais šī pētījuma mērķis bija salīdzināt un noteikt, kuras no konstruktīvajā fibrobetonā izmantotajām tērauda šķiedrām darbojas visefektīvāk. Šķiedru darbības efektivitāte tika noteikta, veicot mikromehāniskus šķiedras izraušanas eksperimentus. Lai adekvāti izvērtētu galvenos šķiedras izraušanas mikromehānismu parametrus,

vispirms problēma tika risināta ar analītisko un skaitlisko modelēšanu. Gala rezultātā tika noteikts, ka viļņotas formas šķiedras fibrobetonā darbojas visefektīvāk, jo tiek pilnībā izmantots tērauda stiprības potenciāls. Eksperimentāli tika pārbaudīta arī betona matricas mehānisko īpašību ietekme un tika secināts, ka ar īsām šķiedrām pastiprinātas matricas efektīvi aizkavē garākas šķiedras izraušanos ārējā spēka iedarbībā.

Pupurs A., Krasnikovs A. Load bearing capacity of steel fibres in concrete

In the present report micromechanics of steel fibre pull-out process in concrete are investigated. The main aim of this study was to determine the type of the commercially available fibres that has the most effective behaviour. The effectiveness of the steel fibres was determined by a single fibre pull-out experiments. Prior to experimental study analytic and numeric modelling was performed in order to evaluate the governing micromechanical parameters of steel fibre and concrete matrix interaction. As a result of this study it was determined that corrugated form fibres are the most effective as the potential of steel strength is fully utilized. Also the influence of concrete matrix properties was analyzed and experimentally evaluated. It was observed that concrete matrix reinforced with additional short steel fibres offer higher resistance to pull-out process of longer steel fibre.

Пупурс А., Красников А. Несущая способность коротких стальных волокон в бетоне

Настоящая статья посвящена изучению микромеханики выдергивания коротких стальных волокон из бетона, таким образом моделируя картину растрескивания и разрушения фибробетонных конструкций. При этом, основной целью исследования ставится выявление марки и формы стальных волокон (среди предлагаемых на рынке), наиболее эффективно армирующих бетон. С этой целью в работе приводятся результаты серии проведенных экспериментов по вытягиванию единичных волокон из бетонной матрицы. Экспериментальные результаты сравниваются с результатами проведенного численного моделирования (используя метод конечных элементов) а также с аналитическим решением (только для случая прямолинейных волокон). Результатом проведенного исследования является вывод о наибольшей эффективности волокон синусоидальной формы, для которых наиболее эффективно используется прочность стали как материала, одновременно с наиболее удачной анкеровкой волокна в бетонной матрице. Показывается, что дополнительное армирование бетонной матрицы вокруг вырываемого волокна более мелкими волокнами приводит к повышению эффективности работы крупного волокна.