

STRESS-STATE ANALYSIS OF FIBRE REINFORCED CONCRETE (FRC)

KONSTRUKTĪVĀ FIBROBETONA SPRIEGUMSTĀVOKĻA ANALĪZE

A.Pupurs, A.Krasnikovs, L.Pakrastinsh

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Introduction

The use of fibre reinforced concrete has experienced a considerable increase during the last decades mainly by virtue of its higher resistance to crack forming and simplified casting technique. However, high internal tensile stress forming requires large fibre percentage in the structural material and adding extra fibres to concrete mix noticeably decreases its workability. In order to maintain a suitable workability fibre percentage in the concrete mix is technologically limited. Today this is the main drawback that prevents competitiveness of fibre reinforced concrete to steel bar reinforced concrete if extensive tension loads are to transmit. Obtaining a FRC mix with high fibre percentage at the same time maintaining technologically suitable workability has been the main aim of many experimental researches carried out.

Considering fibre size to concrete aggregate size ratio, it is clear that analytic or numeric calculations require detailed investigations at the micro-mechanical level. Finite element method (FEM) simulation programs are therefore very convenient. For this study numerical calculations were carried out by FEM program ANSYS [1]. Two-dimensional models were considered suitable for this study.

It is stated and believed in this study that the numerical calculations of stress distribution carried out on fibre reinforced concrete provide a basis on which the analysis of material behaviour can be performed.

The main aim of this study was to investigate stress-state of structural fibre reinforced concrete (FRC) occurring when subjected to external tension loads. Study was aimed to investigate the behaviour of steel fibres of different types and geometrical properties. Overall three different types of fibres have been observed with a subsequent investigation of the influence of steel fibre geometry (fibre length and diameter). A comparison of obtained results has been done. A prediction of potential overload and crack forming areas in concrete due to certain type of fibres present comes as a general conclusion to this numerical study.

Also an object of research in this study was the shrinkage of concrete, which is of great importance when encountering concrete mixes with high fine aggregate percentage. A possibility of considerable internal stress forming in the FRC prior to external loading due to concrete shrinkage was granted. The evaluation of thermal stress forming caused by concrete shrinkage proved significant for complete micro-mechanical analysis.

The obtained results showed both similarities and differences in the behaviour of steel fibres of observed types.

This numerical study was planned as a preface to more complete study which will include not only evaluation of yet more factors like fibre-concrete friction, aggregate size, etc., but also results from experimental investigations. Nevertheless, the results obtained here will serve as a point of reference to all of our following investigations.

Materials

The materials used in this numeric study were defined considering possibilities and expected conditions for following experimental stress-state investigations. Following that, the mechanical properties of concrete were assumed according to the properties of self-compacting concrete (SCC). Self-compacting concrete mixtures are considered essential in obtaining good fibre distribution throughout the concrete volume [2]. Therefore concrete used for experimental investigation was planned to have properties of SCC. It is important to explain here that in order to simplify numeric analysis model for this part of the study, concrete was assumed as homogeneous and isotropic material, which in real conditions never occurs for concrete is known as highly anisotropic and heterogeneous material mainly due to coarse aggregate involved in the concrete mix and its uneven distribution in the matrix. Nevertheless, concrete, which can be classified as self-compacting and which is often used with fibre reinforcement, has a reduced amount of coarse aggregate and therefore concrete matrix gains characteristics of more isotropic and homogeneous material. Although the complete material still cannot be classified as homogeneous at the macroscopic level, in this particular case this aspect is neglected so to simplify the analysis model. Therefore it can be predicted that any of numerically obtained results here will better correspond to concrete without coarse aggregate in the matrix. For concrete where coarse aggregate has been involved in the matrix it is necessary to perform a separate study with the respect to aggregate size and properties of elasticity.

Concrete property values necessary for this particular numeric study were: static modulus of elasticity $E_c=28250 \text{ N/mm}^2$ with respective 28 day compressive strength value of $39,5 \text{ N/mm}^2$; Poisson's ratio $\nu = 0,2$; and shrinkage $\epsilon_s = -0,414 \text{ mm/m}$. All values except Poisson's ratio were taken from investigation study described in [3]. It can be noted, though, that concrete with such compressive strength is high-performance concrete and does not correspond to any of concrete class according to Latvian Building Codes, exceeding compressive strength even of the highest concrete class classified (B 60) in the Codes [4].

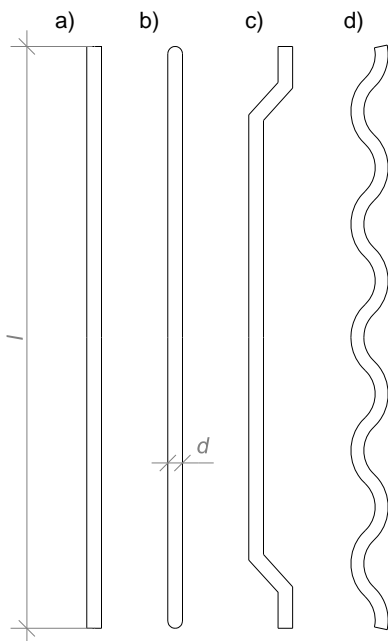


Fig. 1 Types of steel fibres used in experiment

The fibre properties were defined similarly. Essential for the stress-state analysis were geometric and elasticity properties of the steel fibres. Dimensions were obtained from metric measurements applied on fibres. The fibre types observed in this numerical study were straight drawn fibres, Dramix™ fibres with hooked ends and also Wiremix™ fibres with corrugated form. A special case of straight fibre with round shaped endings was studied comparing two equal length and diameter steel fibres but produced by different cutting technologies. Other types of fibres commonly used in building were not observed in this study. It is notable here that one of the aims of the whole study was to investigate behavior of fibres that differ not only by type but also by means of length and cross section.

Therefore an investigation was done researching the character of stress-state using fibres with various lengths and diameters. Fibre length varied between 10 to 50 mm and diameter between 0,3 and 0,9 mm. In order to gain foreseeable results, common characteristic value of fibre length to diameter ratio (l/d) was established on the basis of which the results comparison will be carried out.

Finite element model for tension analysis

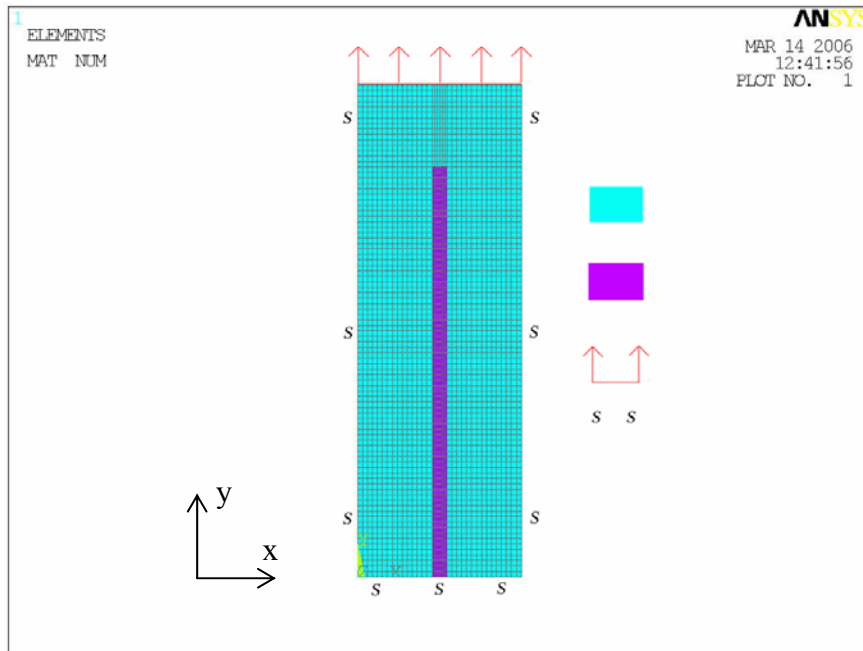


Fig 2. Finite element model for tension analysis

As stated previously, stress-states in fibre reinforced concrete were determined by finite element method simulation model. Finite element program ANSYS [1] was used to carry out the calculations. The model was worked out to represent plane stress case and it consisted of rectangular area of 10 x 60 mm, representing geometric properties of concrete and a separate steel fibre of a certain type (Fig.2). The area dimensions 10 x 60 mm were chosen following the prior estimation of areas

influenced by the presence of separate steel fibre, in other words, only useful, characteristic areas were kept in finite element model built. As it is shown in Fig.2 only half of the material sample was modeled corresponding to model symmetry.

Other data input for tension analysis were elastic properties of the materials, essential for stress-state analysis. Although model area limits were given by the rectangular area (10 x 60 mm), they do not actually represent material limits, because the boundary conditions on area limiting lines were set to represent symmetry boundary conditions (Fig 2.). Therefore the area modeled represents the characteristics of continuous material but not of material specimen with established dimensions.

A separate FEM model was made for each material sample with different fibre type and geometry.

The tension load applied was uniformly distributed load of uniform value in order to simplify calculations. Moreover the correspondence to planned experimental investigations may be later accomplished by multiplying obtained uniform values with the respective value of actually applied load.

The level of finite element mesh fineness was chosen from the point of view of precision of obtainable results therefore a prior investigation was done observing the influence of mesh refinement. It proved to be very important, because in some cases insufficient number of finite elements could have lead to miscalculations. The fineness of mesh in this particular case can be judged observing the mesh around fibre where it was necessary for fibre of diameter 0,9 mm to be divided into 12 finite elements across the diameter.

Finite element model for thermo-elastic analysis.

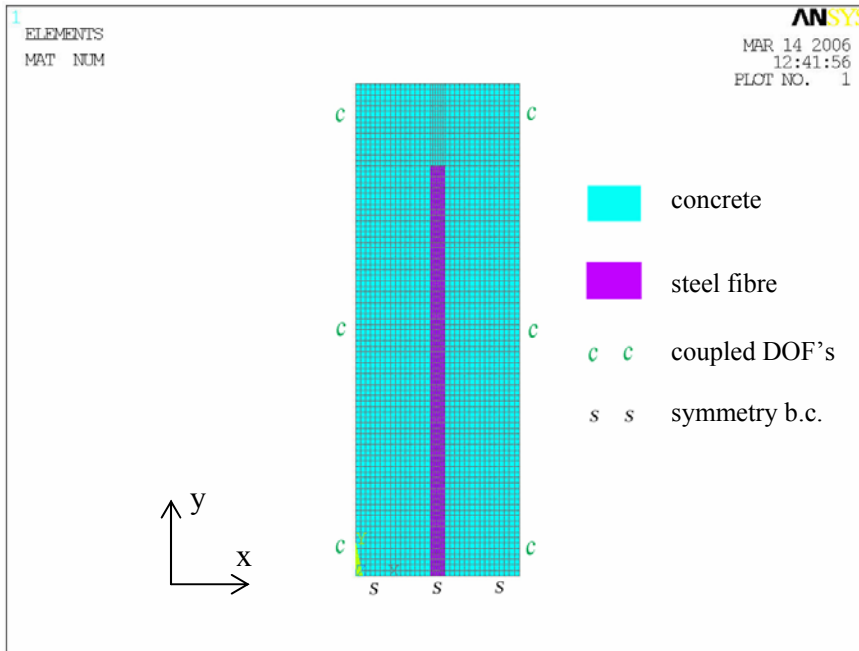


Fig 2. Finite element model for tension analysis

By thermo-elastic analysis the shrinkage stress values were obtained. Model geometry properties were input similarly to the finite element model for tension described previously. The additional parameters necessary for thermo-elastic analysis were thermal conductivity and coefficient of thermal expansion. The coefficient of thermal expansion was calculated following the concrete shrinkage strain value $\epsilon_s = -0,414$ mm/m taken from study described in [3].

Material thermal conductivity values for

concrete and steel respectively were 1,28 and 16,0.

The thermo-elastic analysis carried out by FEM program ANSYS consisted of two parts. At first, thermal analysis was done, where uniform temperature load was applied on all modeled areas including steel fibre model area. The program calculated temperature gradient values for each node of the model. After the thermal analysis the structural part of analysis was done, during which the thermal stress values were obtained. But first, the properties of material elasticity were input. Structural boundary conditions were applied to model according to Fig. 3. As in the previous analysis in tension also here only half of the material sample was modeled, regarding the model symmetry. Coupled degrees of freedom applied on the nodes on sidelines of the model represent that material is continuous but the lines can yet be displaced if caused by the internal shrinkage stress. Reading previously calculated temperature gradients at each node into structural part of analysis completed the thermo-elastic analysis.

The mesh fineness was adjusted in order to match the respective tension model meshes created previously.

Results.

For the simplification of the results analysis expressed it is noted that from this point forward the stress values observed here accord only to concrete. Steel fibre internal stress values are not an object of investigation.

During the analysis (both tension and shrinkage) the stress component results σ_x , σ_y and σ_{xy} were obtained which represent the case of plane stress state. For tension analysis it can be assumed that stress component σ_y is of primer importance because the tension load was applied along axis y (see Fig. 2). However, other components of stress (σ_x and σ_{xy}) are also of significant importance when, for example, providing a precise prediction of micro-crack developing paths.

But for this case σ_y component of total stress was observed first in order to understand the very beginning of concrete overloading process in fibre reinforced concrete. Overlooking the obtained results for tension stress it is obvious that maximum stress component σ_y values are always present in the fibre end zones regardless of fibre type used (Fig. 4)

Observing tension stress-state in FRC when straight fibres with perpendicularly cut endings (marked as “Straight #1” from this point forward) are present (Fig. 4a) it is clearly visible that stress component reaches its maximal value right in the contact zone with steel fibre endings. The same may be addressed also to the case when straight fibres with rounded endings (“Straight #2”) are present (Fig. 4b) in the FRC. However, if we compare the stress-states as they have developed in two material samples in cases when only difference between the samples is the fibre ending geometrical form (all other geometrical and elasticity properties are identical), we can see difference not only in the zone of fibre endings but also in the whole sample (compare Fig. 4a and 4b). In the case with fibres “Straight #1” it looks like a larger area of concrete has been destressed when compared to the case of fibres “Straight #2”. However observing closer the stress distribution right in the contact zone with fibre endings it is visible that rounded fibre ending shape provides more even stress transmission between fibre and concrete than in the case of straight fibre with perpendicular endings, where concentration of high stresses around sharp fibre corners is clearly seen (Fig 4a and 4b enlargement).

In comparison to fibres observed previously fibres with additional ending hooks (marked as “Dramix™” from this point forward) provide even greater destress of concrete area concrete (see Fig. 4c). Due to hooked endings of these fibres it has proved that better concrete-steel fibre cooperation will occur. Moreover the contact zone with fibre endings is still the area most overloaded but less expressively than in cases with both straight fibres (see Fig. 4c enlargement). Also to mention is the fact that the geometrical form of hooked ends does not cause significant stress concentration in concrete near the fibre curves.

With the respect to geometrical form of corrugated form fibres (marked as “Wiremix™”) (see Fig. 4d) it was already predicted before that the character of stress distribution in FRC with such type of fibres present will not resemble to any of the cases observed before. The corrugated fibre form is likely to ensure good cooperation with concrete. And indeed, it proved to be the only fibre that has the capability to cooperate with concrete allover it’s length. While in cases of straight fibres and fibres with hooked endings the main stress was concentrated in the concrete-fibre ending contact zone “Wiremix™” fibres largely tend to distribute maximum stress throughout all the curves (see Fig. 4d enlargement). Although like in all previous cases the governing stress is that which concentrates in the fibre ending zones, it is by far less expressive than in case of both straight fibres and even “Dramix™” fibres. The smoothness of fibre curves also prevents any considerable stress concentration along fibre length.

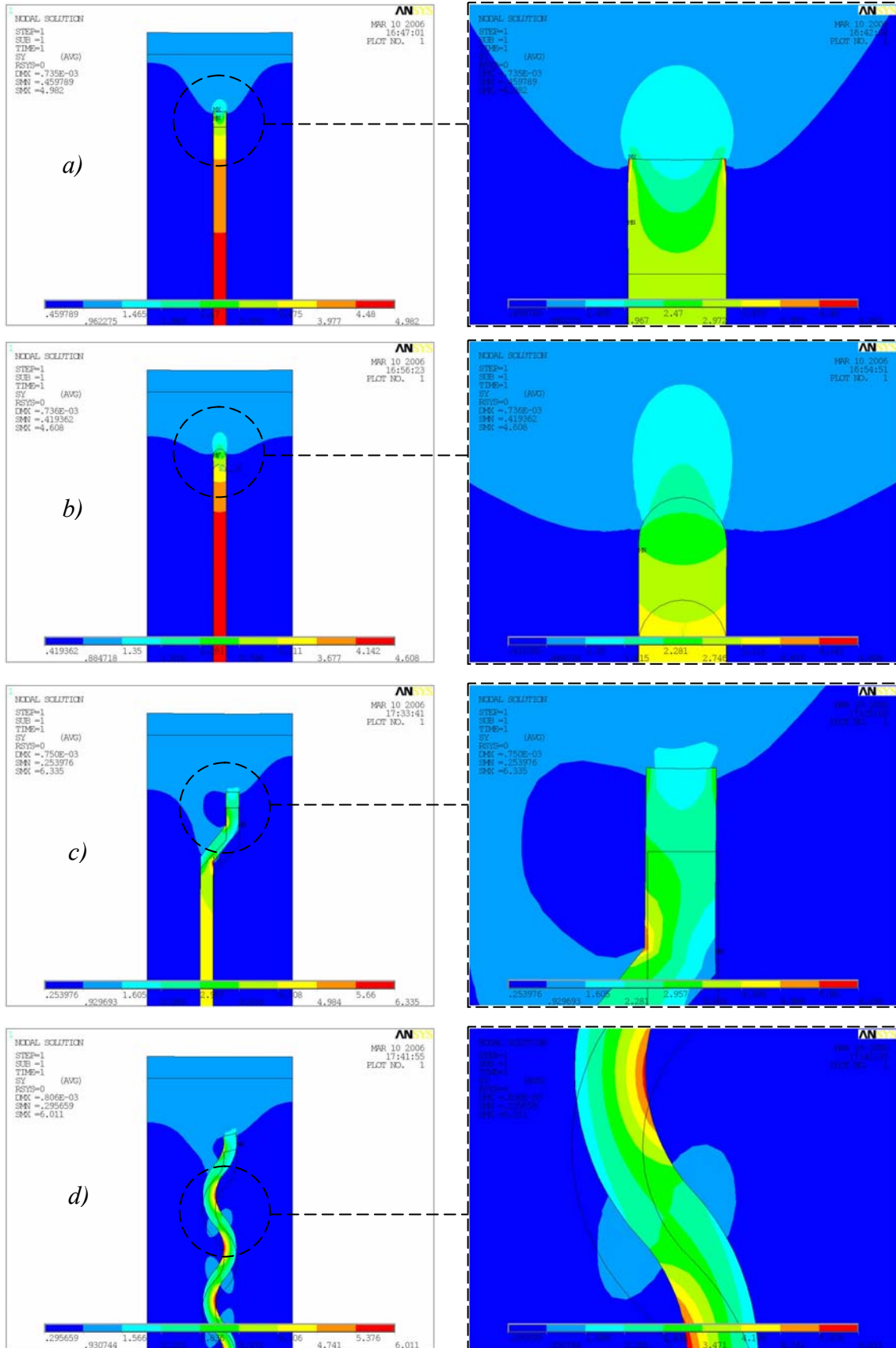


Fig. 4 Tension analysis results. σ_y component of total stress

Equivalent stress.

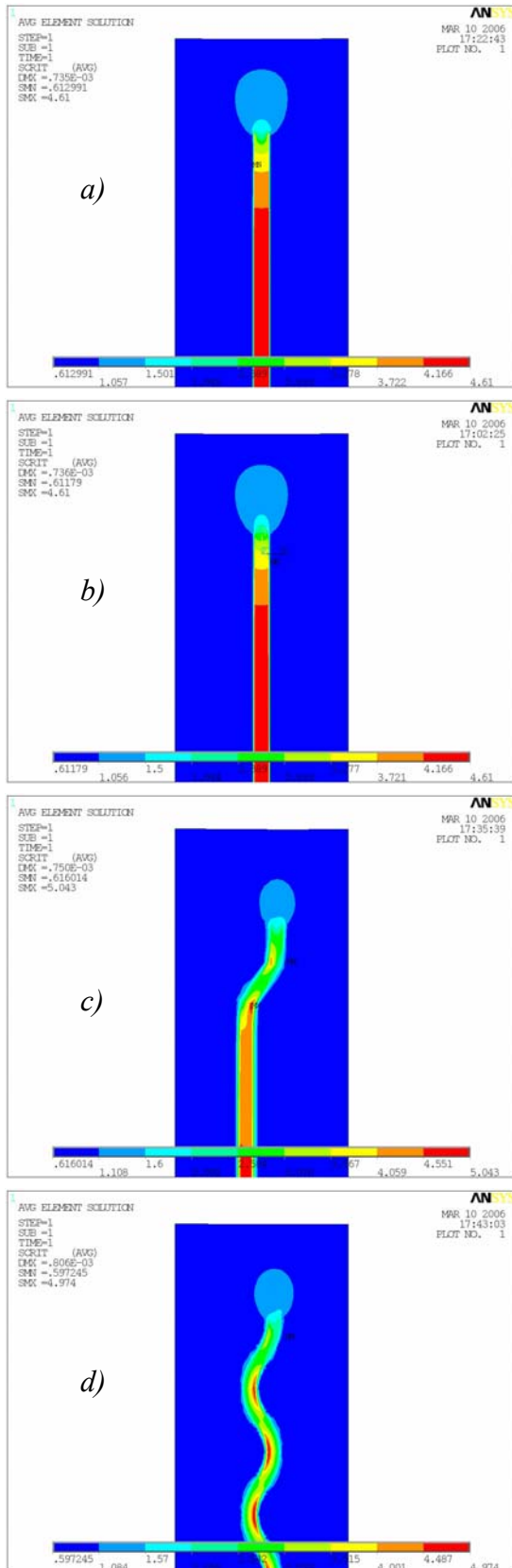


Fig. 5 Tension analysis results.
Equivalent stress σ_{cr}

However, from point of view of material strength, component stress values obtained previously do not provide a general overview. Therefore it is essential for material strength theory to be adapted for further analysis.

Regarding significant difference between fibre and concrete modulus of elasticity it is obvious for steel fibre reinforced concrete that the material rupture will occur due to concrete failure.

It is considered that fourth theory of strength is the most suitable for this case. According to the adapted theory material strength rule is expressed through equivalent stress equation:

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2} \leq [\sigma] \quad (1)$$

For this particular case of plane stress in tension the equation (1) may be expressed as follows:

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 + 3\sigma_{xy}^2} \leq [\sigma] \quad (2)$$

In equation (2) tension stress components σ_x , σ_y and σ_{xy} have already been calculated previously from finite element analysis so equivalent stress σ_e values for each finite element model node are easily obtainable. For graphical representation of equivalent stress values in respective FRC samples see Fig.5. Overlooking the results for equivalent stress values it can be seen that there is a typical governing stress concentration in the concrete and fibre ending contact zone, whereas other concrete zones tend to be less stressed regardless of the fibre type present. While equivalent stress-state character is similar for all cases observed, the only difference between the samples (Fig. 5) is the size and intensity of overload zone. A question may arise why, for example, in the case of “Wiremix™” fibres there is no evident even stress distribution along fibre curves like it was visible when analyzing σ_y component of total stress. The explanation to this fact is that in the case of equivalent stress the difference between stress values at the fibre ending zone and stress values at the fibre middle zone curves is more expressive and therefore visually ignored in the contour plots of equivalent stresses obtained from finite element method program (see Fig. 5 and Fig. 4). Although not visible in the stress plots, the stress distribution actually occurs and must be taken into account when, for example, providing an

explanation why in this case stress intensity is lower than in comparison to other fibre types. The same may be addressed also to the case of “Dramix™” fibres present in the FRC. The respective values of concrete overload coefficient for each type of fibre present are summarized in Table 1. The graphical representation of the same values is shown in Fig. 6.

Table 1. Tension analysis results

Coefficient of concrete overload in tension k_t								
Fibre type	Fibre length/diameter ratio l/d							
	10	20	30	40	50	70	100	160
Straight #1	1,000	1,118	1,141	1,143	1,145	1,240	1,352	1,487
Straight #2	0,830	0,944	0,945	0,948	0,949	1,026	1,117	1,223
Dramix™	0,735	0,803	0,819	0,824	0,833	0,878	0,888	0,963
Wiremix™	0,773	0,821	-	0,823	0,824	0,826	0,828	0,883

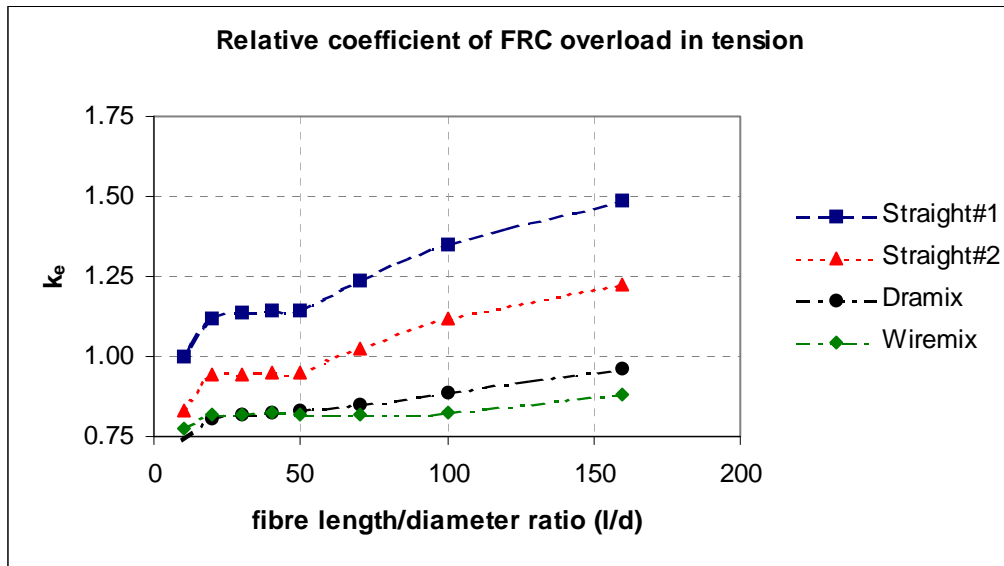


Fig. 6 Fibre behavior in FRC during tension loads

The coefficient of concrete overload was obtained from FEM simulation analysis by processing the results for equivalent stress (equation (2)) and it represents concrete overload in tension with certain type of fibres present. The coefficient was calculated only to provide an entity suitable for fibre behavior comparison. Obtaining of any defined numeric values at this stage of study was not a subject of necessity because this analytic study is still planned to be developed and improved by taking into consideration yet more important factors like steel-concrete friction, cement-mix aggregate size, etc. Therefore coefficient of overload was assumed to be of relative value and was set to 1,000 for the case of fibres “Straight #1” at the fibre length/diameter ratio value 10 and coefficient values for other cases were calculated according to it. Fibre length/diameter ratio was calculated for fibres with lengths varying from 10 to 50 mm and diameter varying from 0,3 to 0,9 mm.

Summarizing the results in Table 1 it is clear that fibres “Straight #1” cause the biggest concrete overload (due to the sharp corners of fibre endings). A common tendency for thinner fibres to cause bigger concrete overload regardless of fibre type is also visible.

Interestingly, the coefficient for “Dramix™” and “Wiremix™” fibres even at highest length/diameter ratio does not reach value 1,000 which accords to fibres “Straight #1” at the lowest l/d ratio observed.

Shrinkage analysis results.

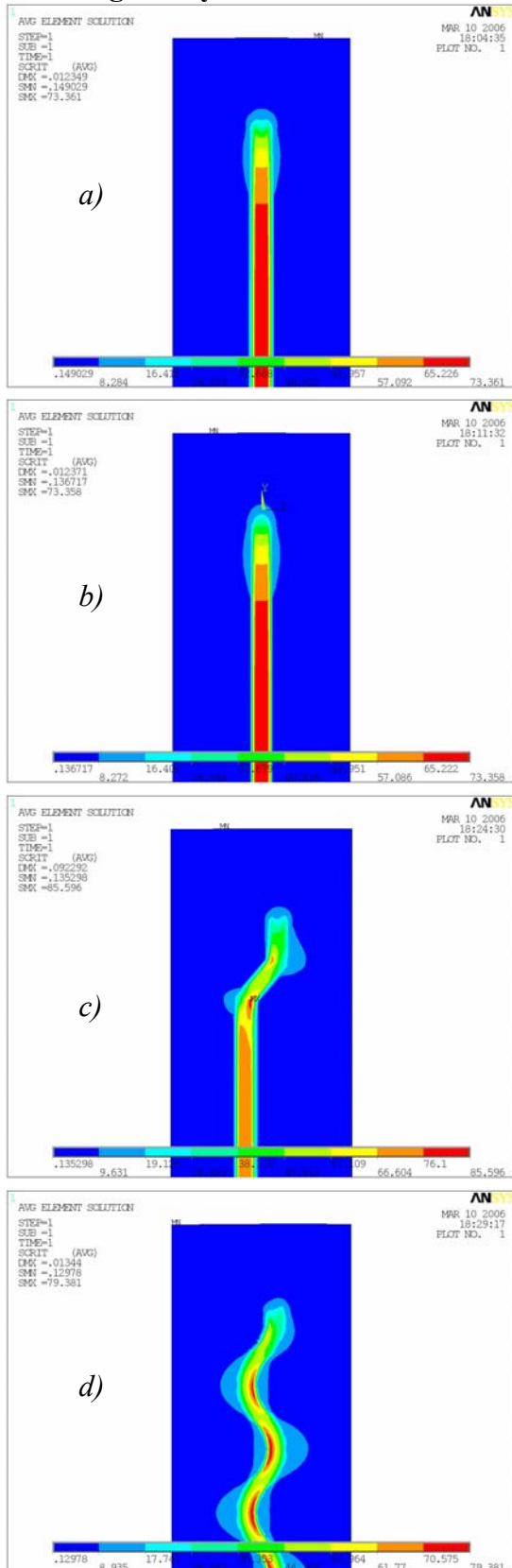


Fig. 7 Shrinkage analysis results.
Equivalent stress σ_{cr}

Following previously stated assertion shrinkage analysis results were also calculated in terms of material strength. The strength theory used was the same as for tension stress analysis and it is expressed through equation (2). Graphical representation of the equivalent stress results obtained is shown in Fig. 7. Overlooking the results it can be concluded again that maximum stress values have been reached at the concrete-fibre ending zones just like it occurred in the previously observed tension stress analysis regardless of the fibre type.

However, considering that shrinkage stress-state differs considerably from the case of tension stress-state, a number of certain diversities had revealed.

In the case of straight fibres (“Straight #1” and “Straight #2”) (Fig. 7a and 7b), while maximum stress distribution character right around the fibre endings is similar to previous case of tension (see Fig. 4a and 4b enlargement), it can be seen that concrete area below fibre ending has also been stressed. Although the stress forming below fibre ending is not the governing, it is still important to notice when predicting potential shrinkage crack forming paths. Comparing the cases of straight fibres again it appears that sharp endings of fibres “Straight #1” cause larger overload than fibres “Straight #2” of the same length and diameter.

If we observe the case of “Dramix™” fibres (Fig. 7c) it is evident that highly stressed zones are either at the fibre endings or near the fibre curves. Unlike it was in tension stress where curves of fibre ending hooks did not cause a significant stress concentration, in shrinkage it is of greater importance. While stress at the fibre endings is still the governing, the stress at fibre curves is also of considerable importance.

Due to the specific geometrical form, it was predicted that the most sophisticated shrinkage stress distribution in FRC would occur with “Wiremix™” fibres present. And indeed, if we look at Fig. 7 it is evident that apart from governing stress, which is concentrated at the fibre ending, a large amount of secondary stresses have distributed along fibre curves. From this point of view it can be concluded that more specific and sophisticated form fibres can cause more significant shrinkage stress concentration.

The respective values of concrete overload coefficient for each type of fibre present are summarized in Table 2. The graphical representation of the same values is shown in Fig. 8

Table2. Shrinkage analysis results

Coefficient of concrete overload in shrinkage k_s								
Fibre type	Fibre length/diameter ratio l/d							
	10	20	30	40	50	70	100	160
Straight #1	1,000	1,165	1,199	1,207	1,205	1,341	1,503	1,698
Straight #2	0,993	1,164	1,199	1,205	1,205	1,341	1,502	1,698
Dramix™	0,923	0,949	0,958	0,988	1,005	1,220	1,315	1,473
Wiremix™	0,922	0,931	-	0,932	0,933	1,024	1,122	1,268

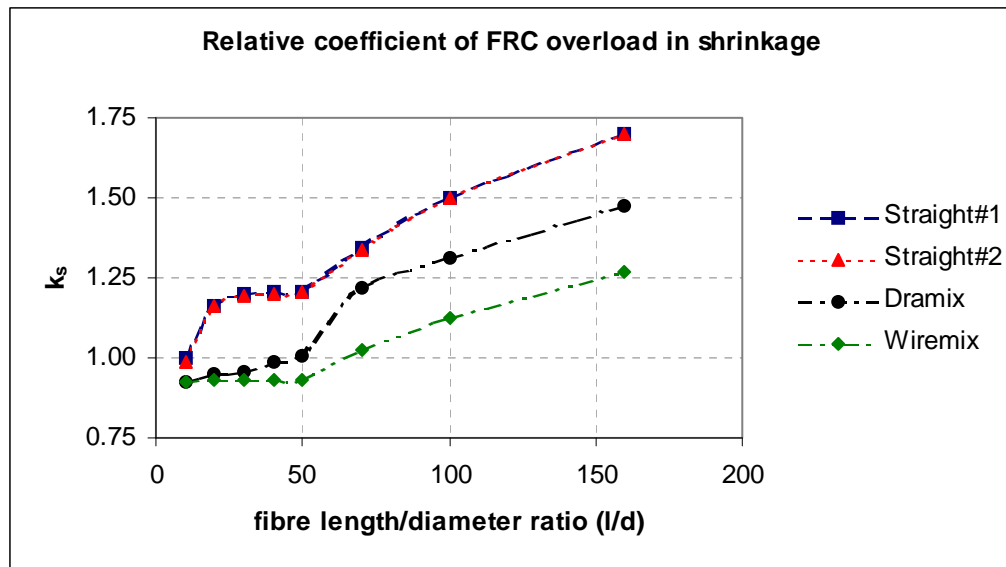


Fig. 8 Fibre behavior in FRC during concrete shrinkage

Like in the case of tension stress analysis the coefficient of concrete overload was obtained from FEM simulation analysis by processing the results for equivalent stress (equation (2)) and it represents concrete overload in shrinkage with certain type of fibres present. The values of calculated coefficient are also of relative values and represent the same relations as described in the case of tension stress. The coefficient of overload was set to value of 1,000 for the case of fibres “Straight #1” at the fibre length/diameter ratio value 10 and coefficient values for other cases were calculated according to it.

Summarizing the results in Table 2 it is clear that both straight fibres “Straight #1” and “Straight #2” cause the biggest concrete overload. The influence of straight fibre ending form (perpendicularly cut or rounded) is not as significant as in the case of tension stress. A common tendency for thinner fibres to cause bigger concrete overload is visible regardless of fibre type.

Without regard to secondary stress concentration near the fibre curves, “Dramix™” fibres still cause less concrete overload in shrinkage if compared to both straight fibres.

However, the lowest coefficient values accord to “Wiremix™” fibres, although significant secondary stresses have concentrated along fibre curves.

In comparison to concrete overload coefficient values in tension (Table 1), the shrinkage coefficient values mutually vary less depending on the fibre type. But it must be noted that this accords only to governing stress, while the presence of secondary stress in shrinkage is more significant than in tension.

Conclusions.

According to the results obtained from this numerical study, where stress-states occurring from shrinkage and tension loads in steel fibre reinforced concrete samples were observed, the following conclusions can be drawn:

The internal stresses reach their maximal values in fibre ending and concrete contact zones both in shrinkage and tension and regardless of the fibre type used in concrete. Therefore the fibre ending and concrete contact zones are certain area for the first micro-cracks to occur.

Rounding straight fibre's endings considerably decreases concrete overload value at the fibre-ending concrete contact zone.

Hooked fibre endings or corrugated fibre forms provide more even tension stress distribution, better cooperation with concrete and less overload in the fibre ending zones, but are a subject of significant shrinkage stress concentration around the fibre curves.

Corrugated fibres proved to be the only of the fibres observed in the study, which cooperate with concrete by the means of whole fibre length.

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Andrejs Pupurs, student for Master's degree
Institute of Structural Engineering and Reconstruction
Riga Technical University
Azenes St 16, Riga LV-1048, Latvia
Phone: + 371 9399515; Fax + 371 7284853
e-mail: andrejs@ozola.bula.lv

Andrejs Krasnikovs, Professor,
Head of Concrete mechanics lab,
Riga Technical University,
Azenes St 16, Riga LV-1048, Latvia
Phone: +371 9436518; Fax: + 371 7089083;
e-mail: akrasn@acad.latnet.lv

Leonids Pakrastinsh, Assistant Professor, Dr.sc.ing.
Institute of Structural Engineering and Reconstruction
Riga Technical University
Azenes St 16, Riga LV-1048, Latvia
Phone: + 371 7089145; Fax + 371 7089121
e-mail: leonidp@latnet.lv

Pupurs A., Krasņikovs A., Pakrastinš L. Konstruktīvā fibrobetona spriegumstāvokļa analīze.

Rakstā ir analizēta stiepes spriegumu sadalīšanās fibrobetonā, ārējo spēku iedarbībā. Spriegumu intensitāte tika aprēķināta ar skaitlisko metodi, izmantojot galīgo elementu metodes datorprogrammu ANSYS. Galvenais šī pētījuma mērķis bija noteikt stiepes spriegumu koncentrēšanās vietas ar tērauda šķiedrām stiegotā fibrobetonā. Tika izpētīts, kā stiepes spriegumu sadalīšanos un intensitāti ietekmē atšķirīgu ģeometrisku formu tērauda šķiedru klātbūtne. Tika apskatīti un salīdzināti fibrobetona modeļi, kas stiegoti ar 3 dažādām tērauda šķiedrām – taisnām šķiedrām, šķiedrām ar papildus gala enkurojumiem, kā arī viļņotas formas tērauda šķiedrām. Papildus izpētīta arī spriegumu vērtību izmaiņa, mainoties šķiedras garumam un diametram. Analīzē tiek ievērtēta arī betona rukuma izraisīto spriegumu esamība, veicot spriegumu aprēķinu visiem modeļiem. Aprēķinot spriegumu vērtības ar atšķirīgām šķiedrām stiegotiem fibrobetona paraugiem, pētījuma gala rezultātā ir izdarīti secinājumi par katras šķiedras kopdarbību ar betonu, savstarpēji salīdzinātas maksimālo spriegumu skaitliskās vērtības, kā arī noteiktas potenciālās pirmo mikroplaisu veidošanās vietas katram aplūkotajam gadījumam.

Pupurs A., Krasņikovs A., Pakrastinsh L. Stress-state analysis of fibre reinforced concrete (FRC).

In Present investigation stress-states analysis was performed for steel fibre reinforced concrete due to external tension loads. 2D numerical calculations were carried out using finite element method simulation program ANSYS. The main aim of this research was to investigate the areas where maximal tension stress values will be reached. Investigation has been done to determine how different types of steel fibres influence stress-states in concrete. Three different fibre types were studied – straight fibres, fibres with hooked edges and corrugated fibres. An additional investigation of fibre length and diameter influence on stress distribution was carried out. Also the factor of concrete shrinkage was taken into account. Maximal tension stress values were calculated for all models, from which the main conclusions were drawn comparing fibre behavior in concrete, stress intensity relations between different models and potential microcrack forming areas.

Пупурс А., Красников А., Пакрастинши Л. Анализ напряженного состояния конструкционного фибробетона.

В статье анализируется распределение растягивающих напряжений в фибробетоне под воздействием внешних сил. Распределения напряжений находились численно, используя метод конечных элементов (на базе программного пакета ANSYS). Целью исследования является нахождение мест концентраций растягивающих напряжений для фибробетона, армированного стальными волокнами (фибрами). Исследовано влияние геометрии стальных волокон на распределение и интенсивность растягивающих напряжений. Рассмотрены три модели фибробетона с различными видами волокон – прямолинейными, с анкерами на концах, а также волнистой формы. Дополнительно исследована величина изменения максимальных напряжений при изменении диаметра и длины волокон. Моделировалось влияние усадочных напряжений. Сделаны выводы относительно особенностей совместной работы отдельных волокон и бетона, произведено сравнение численных значений максимальных напряжений и определены места потенциального образования микротрещин.