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NON-LINEAR POST-CRACKING BEHAVIOUR PREDICTION METHOD FOR HIGH CONCENTRATION STEEL FIBRE REINFORCED CONCRETE (HCSFRC) BEAMS

NELINEĀRĀS DARBĪBAS (PLAISĀŠANAS STADIJĀ) PROGNOZĒŠANAS METODE AUGSTAS KONCENTRĀCIJAS TĒRAUDA ŠĶIEDRU FIBROBETONA SIJĀM

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Introduction

The use of short steel fibres in concrete instead of the traditional reinforcement has been increasingly regarded beneficial in building industry during the past few years. Due to simpler casting procedure significant savings in total construction erection time and cost can be achieved. Improvement of such material properties like toughness, wear and corrosion resistance can also be noted beneficial for steel fibre reinforced concrete (SFRC) comparing to traditionally reinforced concrete structural elements. Although SFRC has been known already since the beginning of previous century, only recent achievements in concrete chemistry (i.e. plasticizers, superplasticizers and the invention of self compacting concrete (SCC)) have opened new possibilities for fibre reinforced concrete with high and ultra high steel fibre concentrations. Due to the fact that steel fibre reinforced concrete with high fibre concentrations (HCSFRC) is a rather recently introduced material in the building industry it is concerned with several drawbacks most of which are the result of some technological shortcomings (i.e., workability, pumpability and homogeneity of the concrete mix) when using mixing, transporting and placing technologies invented for traditional concrete (without fibres). Apart from possible technological drawbacks, the most important issue may be about the structural design of SFRC structural elements. Due to the lack of generally accepted structural design regulations SFRC is often discarded in many potential applications in favour of (most often) traditionally reinforced concrete for which design guidelines are well defined. Up to now only several design recommendations have been introduced for SFRC structural elements mostly with low concentration of steel fibres (up to $70\,kg/m^3$) [1-3], but, unfortunately, there are some mutual disagreements in some of the important statements of available recommendations, e.g. considerably different size factor

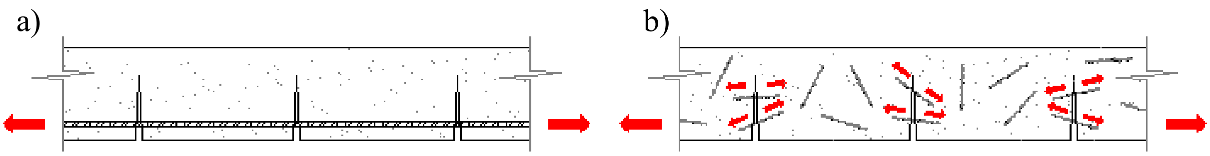

Fig 1. Post cracking behaviour of: a) traditionally reinforced concrete; b) SFRC

values that can cause uncertainty for the designer and doubt the trustworthiness of the proposed design method. Moreover not much is mentioned about fibre concentration in the concrete mix in general.

From the experimental investigations it is known that in bending tests of prisms the typical load-deflection curve for low fibre concentration SFRC elements is considerably different from typical load-deflection curve for HCSFRC elements.

Further on, in many applications a mixture of different types of fibres is used in the same mix regarding that the latest investigations have shown that more effective from the structural point of view is the use of so called "fibre cocktails" – combinations of different length and form fibres in a single mix. The use of "fibre cocktails" results in more dissipated micro-cracking as each type of fibres has its own scale in which it controls the crack propagation. The structural behaviour of the structural element, of course, can differ depending on the composition of "fibre cocktails". Thus in the current situation it is not possible to depend on any published design recommendations as they can not be related for HCSFRC and also SFRC with "fibre cocktails".

The design regulations for traditionally reinforced concrete (with steel rebars) are also not applicable for SFRC structures because of completely different mechanisms that govern the behaviour of each material. Whereas for traditionally reinforced concrete structures the post cracking behaviour is based on tensile strength mechanism (tensile strength of steel reinforcement rebars) for SFRC structures it is the pull-out mechanism of steel fibres from the concrete matrix that determines the load bearing capacity of the cracked material (see Fig.1.). From point of view of mechanics this is the case of long fibre composite material (traditionally reinforced concrete) being compared to short fibre composite (SFRC and HCSFRC).

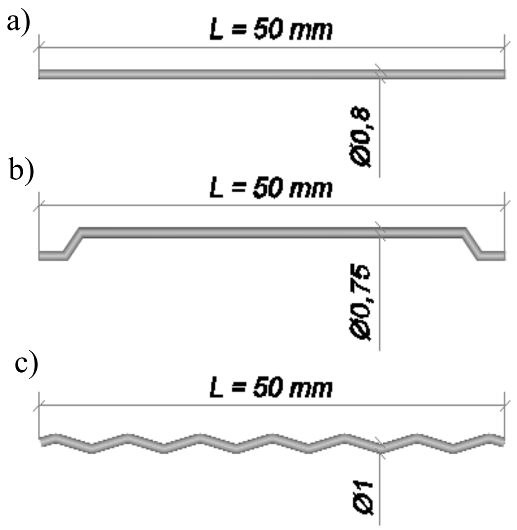

Fig. 2. Steel fibre types: a) straight; b) Dramix fibres; c) Tabix fibres

Therefore it is important to perform a detailed micro-mechanical investigation of fibre pull-out process in order to understand and characterise the behaviour and crack propagation in SFRC structural elements. The mechanical investigations of pull-out mechanisms for different types of steel fibres were performed in study [4] and as a result of it; pull-out laws (pull-load vs. pull-out displacement) for three types (with different geometrical forms) of steel fibres were obtained. Three types were observed in study [4]: straight steel fibres, Dramix fibres (with end hooks) and Tabix fibres - corrugated with round crossection. All of the mentioned steel fibre types have been depicted in Fig.2.

Within this paper a new post-cracking behaviour prediction method is developed and proposed based on previously obtained fibre pull-out laws that were used as the main input data in the new structural behaviour prediction model for beams. Parallel experimental investigations of numerous SFRC and HCSFRC beams subjected to bending loads were also executed with the aim to validate the correlation of all the results obtained by the proposed model.

Determination of fibre pull-out law

As it was previously stated, the results and characteristics of pull-out law experiments for each type of steel fibres were discussed in the paper [4]. Accordingly, in the further studies only those fibre types were used and observed for which the pull-out laws were already known from the previous study [4].

It is known from mechanics that fibre pull-out process is a highly non-linear process initiated by elastic deformation stage which is continued by debonding crack propagation at fibre-matrix interface and concluded by frictional fibre sliding out of the matrix. The parameters influencing each stage of the fibre pull-out process can be different regarding the actual mechanical and geometrical properties of the interacting materials (steel fibre and concrete matrix) and it is often very difficult to formulate analytic relations or to perform adequate numerical simulation of the whole pull-out process. Therefore it was considered that in this case only experimental pull-out investigations would reveal the proceeding of this non-linear process in complete details. Statistically sufficient number of at least five test specimens was therefore prepared. For all specimens the same type of concrete matrix (concrete with 510 kg/m^3 of cement (Cem II)) was used for all types of fibres. As depicted in Fig.3 the test specimens were prepared from a single steel fibre of length 50 mm which was symmetrically embedded in the concrete matrix. As it can be seen in the picture the test specimen is crossed by plastic separator in the specimen midpoint which is also the midpoint of the fibre. Thus an artificial crack is introduced in the specimen with the fibre remaining as the only stress bridging element across it. According to the set-up of the test specimen, when subjected to tensile load, the fibre is expected either to pull out of the matrix in one side of the sample or break at the midpoint. There is also a possibility that the fibre will break after being pulled out for some distance. The pull-out load and corresponding displacement were measured until complete fibre slide-out of matrix.

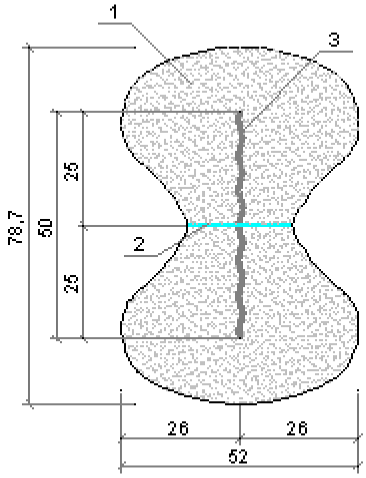

Fig 3. Pull-out test sample set-up:
1) concrete matrix;
2) plastic separator;
3) steel fibre.

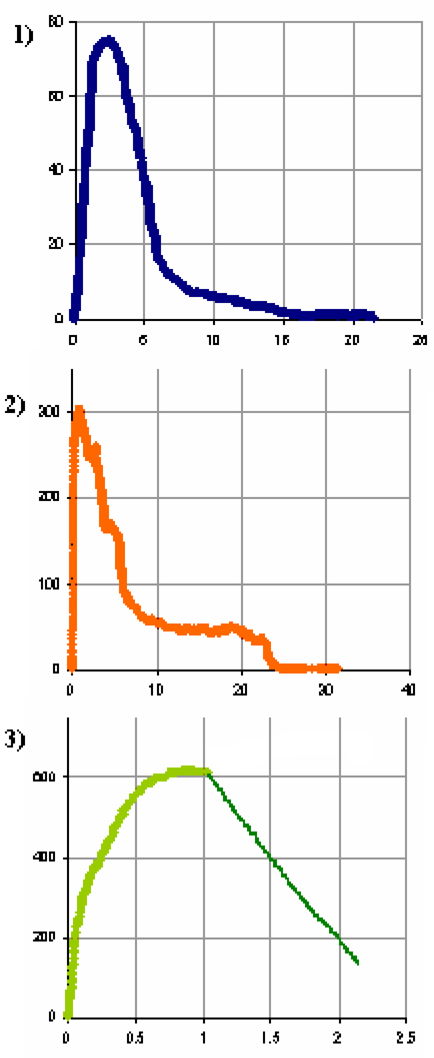

Fig.4. Experimentally determined fibre pull-out law:
1) straight fibres; 2) Dramix fibres; 3) Tabix fibres.
Vertical axis – load in N, horizontal axis – displacement in mm.

The averaged (over the number of experiments for each type of fibres) pull-out load-displacement curves are presented in Fig.4. Pull-out load-displacement curves depend both on concrete matrix properties surrounding the steel fibre as well as the mechanical properties of the steel fibre itself. As it can be seen in Fig.4 both straight fibres and Dramix fibres when subjected to tensile loads were pulled out from the matrix whereas Tabix fibres were broken which means that the strength potential of steel was used completely. The strength capacity for Tabix fibres was reached due to enhanced anchoring capacity regarding the corrugated form of the fibre. It is important to mention here that during simultaneously performed SFRC and HCSFRC (with fibre cocktails) beam tests under bending loads, remarkable micro-cracking occurs around the chaotically oriented fibres and unlike in the pull-out experiment results Tabix fibres are also pulled out of the matrix and no fibre breaking could be observed. It is important to understand and evaluate this disagreement because the fibre pull-out experiment results were planned to be used as an input data for beam behaviour prediction model.

This obstacle was the reason why the determined pull-out law curve for Tabix fibres was approximated based on the observations of actual fibre behaviour in the beam bending tests. The approximation was performed as shown in Fig.4. section 3. It can be seen in the picture that the load-displacement curve obtained experimentally is simply continued by a linearly decreasing relation assuming that in the pull-out process the resistance of fibre decreases with the increase in pull-out distance. The validity of this assumption was not evaluated in this study because the main interest of this particular study was to investigate the new behaviour prediction model in general and to verify whether it is possible to find a simple relation between single fibre pull-out and the crack propagation in structural SFRC beams with different fibre concentrations. It is possible that the simple approximation of the pull-out law resulted in a particular deviation from the actual relation, but it was found out later that it actually had not a major impact.

The results of the pull-out tests show that the average maximal pull-out load for straight fibres is approximately 74 N, for Dramix fibres it is approximately 298 N, but for Tabix fibres it is assumed equal to 620 N, excluding the load at the point of fibre fracture (see Fig.4.). Formally, the pull-out relation values obtained here are valid for only one type of the surrounding concrete matrix as the pull-out laws may differ for different kinds of concrete matrices. Nevertheless also other types of concrete matrices were investigated in beam tests but not a significant difference was observed as the compressive and tensile strength of all concrete matrices was almost the same.

It can be seen from the experimentally obtained curves that the maximal pull-out load for each fibre type corresponds to different pull-out displacement. For example, for straight fibres the maximal pull-out load corresponds to displacement equal to 2,4 mm whereas for Dramix fibres the maximal pull-out load is reached at the displacement value of 0,82 mm.

Table 1. Fibre proportion and amount of ingredients in various SFRC mixes

Nr.	Mix name	Fibre type and amount in kg/m^3					Total amount of fibres in kg/m^3
		Tabix 60, d=1,0	Tabix 50, d=1,0	Dramix 30, d=0,54	Straight 13, d=0,16	Straight 6, d=0,16	
1.	F56	-	127	34	24	10	195
2.	F57	-	127	34	15	20	196
3.	F59	127	-	34	24	10	195
4.	F68	184	-	-	-	-	184

Nr.	Mix name	Amount of the ingredients in kg/m^3					Density kg/m^3
		Cement	Microsilica	Aggregate	Water	Plasticizer (% of cem)	
1.	F56	565	25	1381	224	1,63	2400
2.	F57	568	33	1377	230	1,57	2410
3.	F59	565	25	1446	216	1,56	2470
4.	F68	596	52	1326	210	1,66	2420

It follows from our assumed pull-out law for Tabix fibres that the maximal load 620 N corresponds to 0,87 mm large displacement.

As depicted in Fig.4. the pull-out law for straight fibres is almost linear after the peak-load because only frictional forces at the fibre-matrix interface are able to counteract the applied tensile load. On contrary for Dramix fibres (fibres with end hooks), the post-peak curve is remarkably non-linear, due to additional non-linear processes concerned with local fibre straightening before being completely pulled-out of the concrete matrix. It is very likely, that also for Tabix fibres the post-peak curve would be non-linear as the local straightening of corrugated form fibre should result in even more complicated pull-out character. Nevertheless, in this study at the first approximation, the post-peak curve for Tabix fibres was assumed to be linear as depicted in Fig.4.

As it was already stated, different "fibre cocktail" proportions as well as different concrete matrix types were investigated in this study. Fibre type proportions, the total amount of fibres and ingredient amounts for each matrix are exposed in Table 1.

Principles of the proposed behaviour prediction model

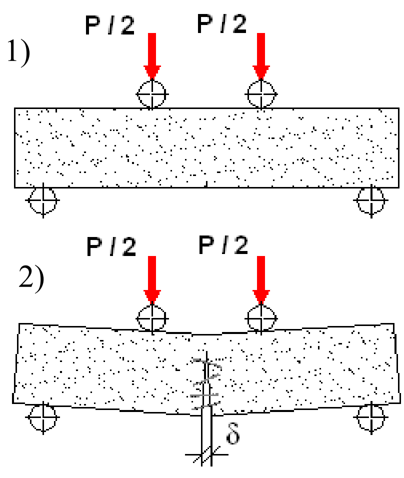

Fig.5. SFRC beam in four point bending test: 1) initial state; 2) post-cracking state

Further, the obtained pull-out laws were used as the main input data for a newly proposed model in order to predict linear and non-linear behaviour of SFRC beams under bending loads. Beams subjected to four point bending were observed in the study as shown in Fig.5. SFRC and HCSFRC structural beams with dimensions $10 \times 10 \times 40$ cm and $15 \times 15 \times 60$ cm were prepared for mechanical testing. Due to high heterogeneity of the material in four point bending it is often difficult to expect the first crack to appear in the midpoint of the beam as the maximal bending moment is constant in the zone between the two loads. Therefore 1 cm deep notch (2 mm thin and cut by diamond saw) was introduced on the bottom side of all beams in this study. The span length of the beam was 30 cm (for $10 \times 10 \times 40$ cm beams) and 50 cm (for $15 \times 15 \times 60$ cm beams). The distance between symmetrically applied loads was 10 cm and 15 cm respectively. The main aim of the proposed model is to predict crack mouth opening displacement δ (crack is now expected to start from the notch) in accordance to the applied bending load P. Simultaneously load – deflection (beam upper surface midpoint vertical displacement) curves were obtained. For this reason displacement transducers were applied on both sides of tested beam to measure the deflection and one displacement transducer was applied on the underside of the beam in order to measure crack mouth opening displacement. Applied load was measured by pressure transducer and synchronized with the displacement and crack opening real-time data by means of multi channel data acquisition system.

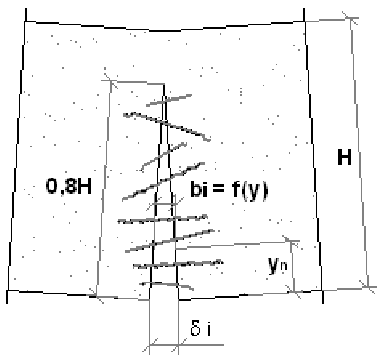

Fig.6. Crack model at beam midpoint

Usually, the non-linear part of SFRC beam behaviour starts with the initiation of cracking process at midpoint of the beam where the maximal bending moment is reached according to the loading scheme used. After the formation of the cracks the stress is still transferred through the crack surfaces by the fibres (the bridging effect). Because the fibres are being pulled out of the concrete matrix, the ability of the SFRC beam to carry the applied load in the post-cracking state purely depends on the capacity of fibres to resist pull-out loads and the exact number of fibres crossing the crack surface (fibre concentration in material). According to the obtained pull-out curves it follows that only for very small values of δ fibre resistance is increasing (especially for straight and Dramix fibres), and after reaching them the maximal value (see. Fig. 4.), fibre resistance to withstand pull-out loads starts to decrease and thus decreases the load bearing capacity of the whole beam itself.

Thus, the behaviour of SFRC beam was modelled by calculating externally applied load P corresponding to maximal crack opening δ at the bottom midpoint of the beam. At the first approximation the model was based on some simple assumptions. Firstly, it was assumed that the total crack height is constant, regardless of size of the crack opening δ. This simple assumption was based on and determined from SFRC beam testing experiments which were performed parallel to the parametric study described here. Thus it was found acceptable for the crack height to be assumed equal to 0,8 of the total beam cross-section height H (see Fig.5.). As it can be seen from Fig.5, the crack planes have been assumed linear therefore the local crack opening b_i can be determined by a simple relation from corresponding maximal crack opening value δ_i.

The procedure of modelling beam behaviour in bending was performed according to step sequence, with the maximal crack opening δ values within the range from 0,2 to 6 mm with the step 0,2 mm.

At each step "i" with the corresponding maximal crack opening δ_i, firstly the local crack opening b_i was calculated as a function of distance y_n:

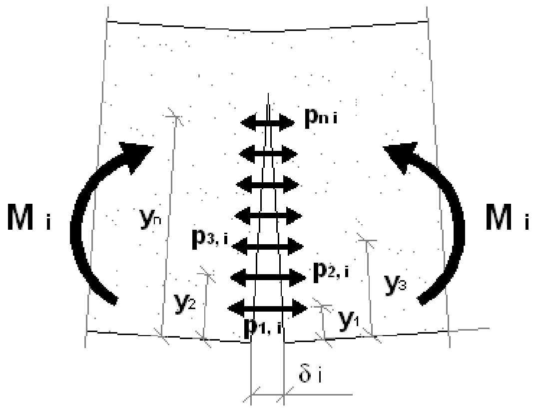

Fig 7. Scheme of internal forces and moments formed in SFRC beam at post-cracking stage.

$$b_i = f(y_n) \quad (1)$$

As the local crack opening b_i is known at each distance y_n, the force p_i transferred through the crack can be calculated by using absolute values from previously obtained fibre pull-out laws. However, this is the point when factors of fibre size (length l, diameter d), fibre volume fraction V_m, fibre orientation factor α should be evaluated thus referring to actual properties of the particular material. The volume fraction V_f of each fibre type could be easily determined from corresponding fibre weight fraction W_f. Further, number of each type of fibres on one cross-section unit was determined, multiplying the average fibre area fraction with fibre orientation factor α which in this case was assumed equal to 0,3 (for chaotically oriented fibres in all tested SFRC beams). The influence of fibre type, fraction and orientation actually can be summarised within one coefficient, which in this case is defined as fibre factor k_f:

$$k_f = f(l, d, V_f, \alpha) \quad (2)$$

Now the internal force transferred through the crack can be calculated. From the pull-out law curves the force $p_{n,i}$ corresponding to a particular crack opening b_i can be determined all along the crack height as schematically depicted in Fig.6. As it can be seen in the figure the internal force $p_{n,i}$ was calculated at corresponding value of coordinate y_n with the increment $y_{n+1} - y_n = 1$ cm:

$$p_{n,i} = f(y_n, \delta_i) \quad (3)$$

From the calculated values of internal forces $p_{n,i}$, resulting bending moment M_i can be determined corresponding to each crack opening value δ_i. According to accepted modelling assumptions it follows that:

$$M_i = \sum_{n=1}^{m} 2 \cdot p_{n,i} \cdot (0{,}8 \cdot H - y_n) \quad (4)$$

When the internal bending moment value is known, the corresponding external force P_i can be calculated from the simple equilibrium relations according to the scheme in Fig.5:

$$P_i(\delta_i) = 2 \cdot M_i / L \quad (5)$$

where L is the span length of the beam. Relation of externally applied load P as a function of crack opening displacement δ is thus obtained at each step and can be represented graphically. The force P represents total force applied to the beam that is divided in two symmetrical forces as shown in Fig.5. To run the algorithms of the model described previously, specific computer software was used.

Results and discussion

As it was described previously, the proposed model was applied for behaviour prediction of SFRC and HCSFRC beams with various fibre concentrations. In this case SFRC and HCSFRC mixes with fibre concentration within the range from 200 kg/m^3 to 300 kg/m^3 were studied. To evaluate the validity of the proposed model, parallel experimental testing was performed according to the same loading conditions as for modelling. Figures 8-11 represent some relevant modelling results being also compared with the experimental data for the same material. It is important to note here that the experimental curve represents only one sample of the specific mix therefore the agreement with modelled results can vary as it can be seen in figures 8-11. The results for four different concrete mixes have been presented. As it is evident from all the plots, the newly proposed model succeeded to agree with the experimental results regardless of the simplicity of the modelling approach. At this point the model may not provide the best agreement in numeric values between modelled and experimental results because of the high scatter between different samples of the same concrete mix composition, but character-wise it is obvious that predicted behaviour curves are in very good agreement. Not presented in the figures are the plots where the actual crack propagation character during experimental testing was in contradiction to modelling assumptions e.g. in the cases where during four point bending tests the crack started to propagate in the tension zone at the point where load $P/2$ was applied and not at the beam midpoint. That is in conflict with the assumption of crack propagating from the beam midpoint notch.

The predicted values in such cases differed considerably because in fact the displacement transducer was situated in the zone where the crack did not propagate. In all other cases presented in Figures 8-11 the crack propagation during the bending test was in accordance to the principles of the proposed model and therefore visibly better agreement between the curves was obtained.

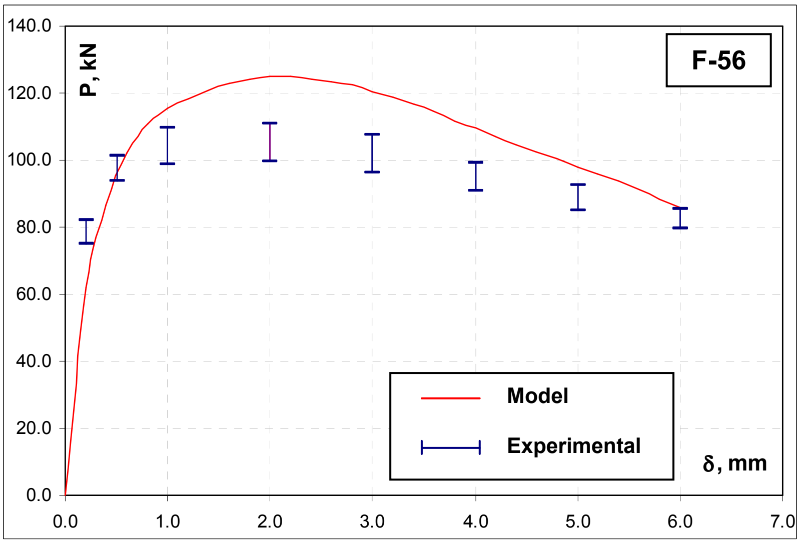

Fig.8. Modelling and exparimental bending test results for mix F-56

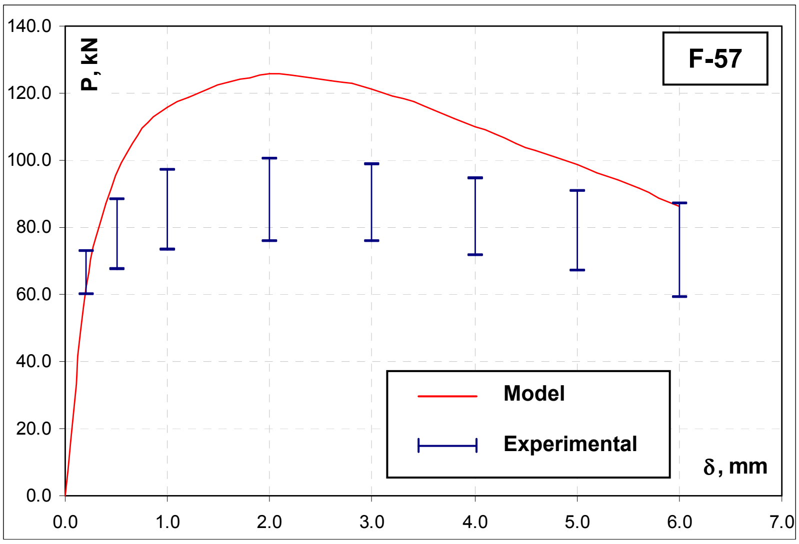

Fig.9. Modelling and exparimental bending test results for mix F-57

It can be understood from the obtained results comparison that the behaviour prediction model gives higher load bearing capacity values than showings of average experimentally obtained testing results for beams with the same composition. In fact, the modelled curve values are usually in very good agreement with the highest experimentally obtained curve from the whole tested specimen batch whereas the rest of the experimentally obtained curves and also the average experimental curve for batch show lower values. It may be concluded that the agreement of modelled results with the experimentally obtained data is highly dependant of the scatter of experimental results which in its turn depends on the homogeneity of the concrete mix used during the beam preparation.

No significant dependence of result agreements on fibre concentration was found within the observed range (195 – 310 kg/m^3). Therefore the obtained results allow us to conclude that the proposed model is valid for behaviour prediction of SFRC beams with any fibre concentration fitting within this range.

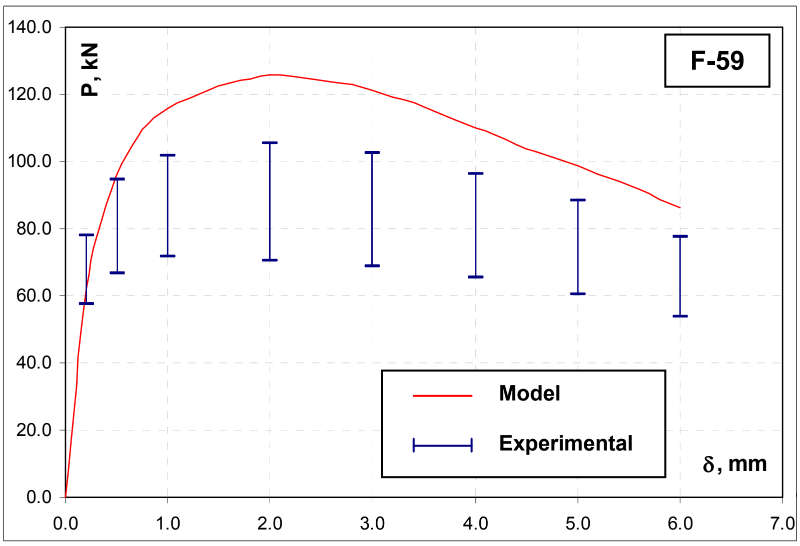

Fig.10. Modelling and exparimental bending test results for mix F-59

The model presented here should be updated with more micro-mechanical experiment results where different fibre angles and embedded lengths are observed. This would result in more representative input data and possibly a better correlation with experimentally obtained load-crack opening curve. The quality of the SFRC and HCSFRC beam samples should also be evaluated and a smaller scatter should be gained from the experimental testing. These are the issues to be solved first in the next step of developing the proposed model.

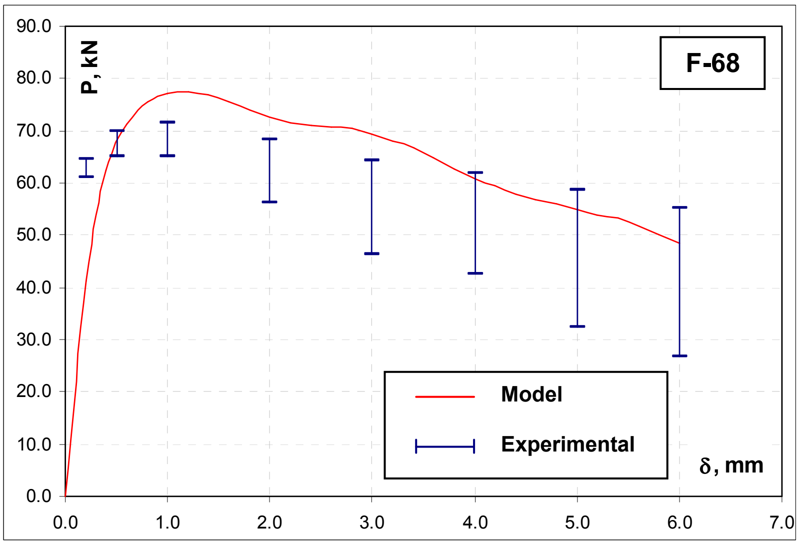

Fig.11. Modelling and exparimental bending test results for mix F-68

Conclusions

As a result of the present study several important conclusions were drawn:

1. Modelling results from the proposed SFRC beam behaviour prediction method proved to be in a good agreement character-wise with experimentally obtained values although the deviation of individual test results is not excluded.
2. Good agreement with the experimental results confirms that the main non-linear micro-mechanisms have been successfully comprehended and applied in the proposed model.
3. The proposed beam behaviour prediction model proved to be valid despite the rather simple approach and assumptions.
4. The validity of the proposed model has been proved for SFRC beams with fibre concentrations up to 310 kg/m^3

Acknowledgements

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Pupurs A., Krasņikovs A., Kononova O., Šahmenko G. Nelineārās darbības (plaisašanas stadijā) prognozēšanas metode augstas koncentrācijas tērauda šķiedru fibrobetona sijām

Ziņojumā aprakstīts jauns modelis konstruktīvā tērauda šķiedru fibrobetona (SFRC) siju darba prognozēšanai. Piedāvātā metode aptver gan lineāro, gan nelineāro pēc plaisāšanas darba stadiju tērauda šķiedru fibrobetona sijām lieces slogojumā. Iepriekš veiktajos pētījumos tika novērots, ka galvenais mehānisms, kas nosaka sijas darbību nelineārajā stadijā ir šķiedru izraušanās no betona matricas. Tādējādi piedāvātās metodes pamatprincipi tika izstrādāti balstoties uz šķiedru pretestību izraušanas spēkiem. Modelēšanas teorētiskie rezultāti tika salīdzināti ar eksperimentāli iegūtiem siju pārbaužu datiem un novērota rezultātu laba sakrītība. Iegūtie rezultāti liecina, ka piedāvātais modelis ir lietojams SFRC siju darba prognozēšanai fibru koncentrāciju diapazonā 195 – 310 kg/m^3. Secināts, ka galvenie mikromehānismi sekmīgi ir novērtēti un pielietoti šajā modelī.

Pupurs A., Krasnikovs A., Kononova O., Shakhmenko G. Non-linear post-cracking behaviour prediction method for high concentration steel fibre reinforced concrete (HCSFRC) beams

In the present report a new method for behaviour prediction of steel fibre reinforced concrete (SFRC) beams is presented. The proposed method is related to both linear and non-linear (post-cracking) behaviour of SFRC beams subjected to bending loads. During the previous investigations it was observed that the main mechanism in the non-linear stage of SFRC beam behaviour is steel fibre pull-out from the concrete matrix. Therefore the principles of the proposed method were based on pull-out load resisting capacity of steel fibres. The modelling results were compared with experimentally obtained SFRC beam tests and they showed good agreement. The obtained results show that the proposed model is valid for behaviour prediction of SFRC beams with fibre concentration within the range 195 – 310 kg/m^3. Therefore it can be concluded that the main micro-mechanisms were successfully evaluated and applied in the model.

Пупурс А., Красниковс А., Кононова О, Шахменко Г. Метод прогнозирования работы бетонных балок, армированных стальными волокнами высокой концентрации в нелинейной стадии после образования трещин

В данной статье представлен новый метод прогнозирования работы фибробетонных балок, армированных стальными волокнами. Предлагаемый метод включает в себя как линейную, так и нелинейную (после появления трещин) стадию работу балок, подверженных изгибающей

нагрузке. Предварительно проведенные испытания показали, что в нелинейной стадии доминирует механизм выдергивания волокон из бетонной матрицы. Поэтому принципы предложенного метода базируются на учете сопротивления стальных фибр выдергиванию. Получены хорошие схождения между теоретическими результатами моделирования и экспериментальными данными испытаний балок. Полученные результаты позволяют использовать модель для концентрации волокон 195-310 кг/м^3. Основные микромеханизмы были успешно использованы в данной модели.