OPTIMIZATION OF FIBER REINFORCED CONCRETE STRUCTURAL MEMBERS

KOHOUTKOVÁ Alena [1]

Abstract

Enhancement of function and performance of selected precast structural members by replacing ordinary reinforced concrete by fibre reinforced concrete being supported by transfer of innovative technologies from laboratory in academic sphere into real industrial production conditions brings about questions how to optimize the entire procedure, what type of FRC to utilize and how to manage production so that it is cost-effective and results in savings of labour and material.

The principles of well accomplished design of fibre reinforced concrete structure as a complex demanding process. Multi-criteria optimization of the production of the structural member starts from proportioning the best concrete mixture with fibres. It is done by means of an efficient tool based on an expert's judgment system. It is verified by experimental investigations and numerical simulation of structural performance.

Keywords: fibre reinforced concrete; multi-criteria optimization; design of FRC structural members

1. Introduction

Fibres in a structure affect resulting properties of concrete composites and improve structural behaviour under service load, fatigue resistance, prolong service life and provide advantageous failure mechanism due to higher ductility. Due to fibres the amount of shear reinforcement may be reduced [1]. Significance of fibres is not only in enhancement of the performance of FRC in comparison to the plain concrete but also in synergy of fibre reinforced concrete with steel bar reinforcement in reinforced concrete structures or with prestressing in prestressed structures [2]. Fibres have their irreplaceable function in high strength concretes [3] and ultra high strength/high performance concretes. For effective application of FRC in structural members it is necessary to ensure both appropriate technique for production and adequate guidelines for design.

2. Design and optimization

Optimum design of a structural member made of FRC insists in two basic principles:

[1] KOHOUTKOVA Alena, CTU in Prague, Fac. of Civ. Eng., Thákurova 7, 16629 Prague 6, email: akohout@fsv.cvut.cz

Each type of FRC is specific and original and its performance depends on components used in the mix design. The most effective type of FRC can be found and match a properly defined function of the certain structural member. Performance of the specific FRC member can be defined by means of properties such as compressive strength, tensile strength, ductility or toughness. Relation between properties and mix components can be found and quantified by a special procedure.

2.1 Components of fibre reinforced concrete

The overall task was to define the procedure of optimization technique of production for the best performance of the given concrete member. It is necessary to determine a set of characteristics like strength, durability, ductility, toughness, amount of materials, type of fibres, labour, time, cost – most of them are in positive or negative correlation - and decide which parameters will be subject to optimization. This set will represent best performance of the future member. The first step is to evaluate properly a set of various mixtures of FRC in relation to preselected characteristics and comparison of their performance with defined best performance. The routine manipulates inputs within the limits given by previous skills and experience gained by the research team in long-term FRC experimental investigations and a valuable database of performed test results. The inputs can be assigned importance weight coefficients according to appreciation of the user. Repeated procedure results in of the optimal solution. A basic routine facilitates and accelerates the mixture design of FRC.

2.2 Multi criteria optimization of the FRC design

The routine was applied for design of various groups of precast concrete members intended for application. It was necessary to choose most efficient type of FRC with suitable mixture composition. Two types of precast elements were inquired in different applications; a precast plate element and precast column of crash-barrier wall system. The reasons were differences in loadings and conditions acting on elements during their service life. The result of the study was that concrete with synthetic fibres was better solution in one case and concrete with steel fibres was the more suitable material for the other type of members. Both groups showed greater toughness and increased tensile strength in comparison to plain concrete. All selected fibre reinforced concrete materials have good ductility needed for elements exposed to severe conditions in transportation construction concerning loads and changes of temperature and humidity including influence of deicing means.In both cases optimization technique in detail was used and verified. Full-scale tests and numerical simulations of the precast members were performed within the research project. From the overall results can be seen that optimized members with suitable type of fibre reinforced concrete led to increased resistance of both plates and columns compared to the original concrete members. Load at the first crack of the investigated concrete columns was much higher than that of original concrete column.

2.3 Tool for design of a FRC structure

The structural analysis of a particular structure or structural element would consist of preliminary analysis where the stress-state of the element due to loading would be calculated. On the basis of required properties of the structure and database of material properties convenient concrete mixture would be chosen and numerical simulation performed to predict behaviour of the structure. Finding of optimal proportion of fibres for any application in terms of Performance Based Design would be decisive. An optimization problem is solved to meet demanded properties and to design a realistic mixture with good workability at favourable price. The advantage is that it is not necessary to test different types of concretes in a laboratory, what saves time and money. When proper FRC is found, the second phase of design is applied. During this phase selected characteristics of the real member manufactured in the plant are optimised: shape and amount of material, time of production, labour resulted in optimal performance for optimal price.

3. Applied examples

A case study within the project was developed for choice of parameters for different groups of structural members. Parameters of simulation depend on the type of the structure, namely if the reliability of the structure depends on the behaviour before cracking or soon after cracking and on acceptable simplification of the structure.

In the project conducted within the frame of the project supported by the Ministry of industry and trade in cooperation with construction industry concerning design methods and practical application of various types of fibre reinforced concrete several types of simple precast members for bridge covering and auxiliary use in the sphere of bridge construction were selected for testing in the production plant.

3.1 Precast FRC elements

For more sets of precast concrete members intended for application of FRC the main goal was to choose efficient type of fibre reinforced concrete with suitable mix composition. Several types of precast elements were inquired in different applications; plate precast bridge surface and accessory elements and precast crash-barrier members. The reasons were differences in loadings and conditions acting on elements during their service life so that optimisation had different parameters.

Fig. 1: Casting of FRC member; (b) lifting from the formwork

A structural analysis was carried out to provide the load-bearing capacity of the plate members to be able to carry all the loads with lower conventional reinforcement. The thickness of the member was smaller and therefore the weight decreased and the overall dimensions of the element were optimized. Cost on the more expensive material due to cost of fibres was compensated by decreasing of lower total volume of the member, by partial removal of conventional rebar reinforcement and by cutting down of armouring labour (Fig. 1). The cost on transport and handling was also lower due to lower self weight. The FRC members are cost-effective due to lower consumption of material and energy. Mechanical resistance of the plates during transport and manipulation were verified in applications on several sites (Fig. 2).

3.2 Prestressed FRC elements

The experimental research included modification of precast column members for noise barrier reinforced concrete wall system and verification of SFRC prestressed girder without conventional rebar reinforcement intended for footbridges.

The columns have I-shaped cross-section what enable supporting of horizontal panels. The columns are manufactured in lengths from two to six meters according to local conditions on the final position and other requirements. Current precast columns were made from reinforced concrete with conventional steel bar reinforcement. The investigations enquired possibilities of the reduction of rebar reinforcement in the element with combined (rebar – dispersed) reinforcement and if it would be cost-effective. The feasibility of production of prestressed columns with and without dispersed fibre reinforcement was verified too. The dispersed reinforcement was assumed in two variants – steel fibres and synthetic fibres. SFRC was chosen in cases where the increase of tensile strength and residual tensile strength were demanded, synthetic fibres were chosen for the increase of toughness and resistance to stroke damage. Mixtures that would not impede the production and would not affect the traditional technology of production were designed. Workability was tested, standard laboratory tests were performed and strengths determined. Full-scale tests and numerical simulations of the pre-cast columns were performed within the research project.

The girder has a solid cross-section with dimensions of 400 mm x 1000 mm. The decision to design compact element was given by the demand of producer that the footbridge shall embody only pre-stressed reinforcement without any other rebar reinforcement.

Fig. 2: (a, b) Storage of the precast plate elements

Minimizing of conventional bounded rebar reinforcement diminishes workability and time consumption in the manufacturing of the element and thus the manufacturing becomes cheaper.

4. Results

The prediction of a realistic life cycle and the prolongation of the service life is an important task to reduce costs of structures in the future. The precise assessment of the life cycle has become an important challenge. Assessing the state of the structure must precede every life cycle determination. The actual and future trend in safety assessment is the use of reliability-based methods for structural assessment.

Fig. 3: Testing of prestressed elements, a) column, b) girder

The laboratory tests and tests in the plant (Fig. 3).showed higher resistance than the theoretical analysis In the analysis of executed tests several reasons of the differences were pronounced. Performed tests, calculations and simulations show that prestressed columns have higher resistance than the reinforced concrete columns; at the same time the failure mode is acceptable and safe. For the tested length of columns are the prestressed columns reliable even without additional shear reinforcement or dispersed reinforcement.

Yet the fibre reinforcement is assumed to enhance toughness, reliability and resistance to damage during transport and manipulation and also durability in severe conditions. Moreover, health and environmental aspects must not be ignored. Extensive research activities in this area were summarized. Further investigation will be necessary to define safety limits for exposure and their life cycle in the nature. Infrastructure maintenance has traditionally been governed by optimization of economical, serviceability and safety issues. In last decades additional issues are born from recognized needs of sustainable development and life cycle analysis. The software described and used for optimising constituents in the FRC mixtures proved to be cost effective and efficient tool in three given working examples. Utilization of this tool can improve applications from FRC.

Generally, the FRC characteristics for tension largely influence the bending resistance and the shear resistance properties of the structure. By estimating tensile characteristics adequately, it is encouraged to produce the structure with efficient safety and also with the economical rationality.

When proposing the suitable methodology for FRC structures design, demands on FRC analysis were stated. Designing of FRC elements is compatible to general concrete structures analysis. Benefits of fiber reinforced concrete are taken into account. A general routine for FRC member is now established. There are many types of fibers and concretes with diverse behavior. These are the reasons to propose methodology as simple and as low-cost as possible.

Analysis of any FRC structure is based on realistic material properties and suitable material model. The basic material characteristics are determined in common laboratory tests: in compression, in tension, in flexure and proper additional ones.

5. Conclusions

A cost-effective design of fibre reinforced concrete is a complex and demanding process. The presented tool can accelerate the process of developing FRC suitable for selected member application and enables further optimisation of FRC manufacturing processes, production in precast plants as well as in-situ FRC elements may increase saving potential so that the construction costs will decrease and the user spending will be fully exploited. Innovation consisted in a transition from current concrete to fibre reinforced concrete when an optimization procedure is necessary: starting from selection of proper type of fibre reinforced concrete mixture, adjusting shape and weight of the member and experimental verification of structural behaviour of the new member accompanying with sets of additional tests including long-term behaviour modelling and durability simulation. The manufacturing in the real factory conditions was verified and successful production of members was started.

Acknowledgements

This outcome has been achieved with the financial support of the Ministry of Industry and Trade of the Czech Republic, project No. FR-TI2/496, and support of the Technology Agency of the Czech Republic Project No TE01020168 is also gratefully acknowledged.

References

[1] Kohoutková, A. - Broukalová, I. - Krátký, J. - Vodička, J.: Experimental and Numerical Research of Fibre Reinforced Concrete Beams, In: Harnessing Fibres for Concrete Con-struction. Bracknell: IHS BRE Press, 2008, p. 163-171. ISBN 978-1-84806-042-5.

[2] Kohoutková, A. - Broukalová, I.:Concrete Behaviour and Crack Control of Prestressed Concrete Beams with Fibres, In: 8th RILEM International Symposium on Fibre Reinforced Concrete: Challenges and Opportunities Guimaraes: University of Minho, 2012, ISBN 978-2-35158-133-9.

[3] Foglar, M. - Kovar, M. - Kohoutková, A.: Experimental testing of blast resistance FRC and RC bridges, In: Bridge Maintenance, Safety, Management, Resilience and Sustainability London: Taylor and Francis, 2012, p. 3044-3051. ISBN 978-0-415-62124-3.