RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Mechanics

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Candidate for a Doctoral Degree of the Study Programme "Mechanical Engineering"

GLASS FIBRE KNITTED REINFORCEMENT FOR COMPOSITE MATERIALS

Summary of Doctoral Thesis

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DOCTORAL THESIS
PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis is to be defended publicly on 8th June 2015 — 2 p.m., at the Faculty of Transport and Mechanical Engineering of Riga Technical University, 6k Ezermalas Str., Room No. 302.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to other scientific degree.

Galina Harjkova …………………………….

Date: ………………………

The Doctoral Thesis has been written in the Latvian language. It contains introduction, 4 chapters, conclusions, bibliography with 192 reference sources, 4 appendices; it has been illustrated by 115 figures. The volume of the Doctoral Thesis is 160 pages.

CONTENTS

GENERAL DESCRIPTION OF THE RESEARCH

Topicality of the Doctoral Thesis

In recent years, knitted fabric has received great attention as reinforcement in various industries. Comparing with classic laminates, knitted reinforcements show better interlaminar shear resistance, good deformability and formability that makes such a kind of material suitable for manufacturing details of complex shapes. Prediction and calculation of mechanical properties — strength and elastic constants — can be difficult. In the present research, polymer matrix and cementitious matrix composites with knitted fabric reinforcement will be analysed.

The Aims and Tasks of the Research

Main **aims** of the research are as follows:

- To analyse composites with plain weft-knitted reinforcement;
- To explore specifics of micromechanics and deformation mechanism for knitted fabric and their composites;
- To calculate mechanical properties (namely elastic constants and strength);
- To analyse accuracy and adequacy of used methods.

To achieve the aims, the following **main tasks** are to be accomplished:

- To overview literature regarding research topic, to analyse applicable modelling approaches and existing models and methods;
- To prepare samples;
- To experimentally determine material (with polymer and cementitious matrices) properties;
- To find effective ways for the modelling of mechanical properties;
- To analytically determine mechanical properties;
- To create models and simulate mechanical behaviour;
- To compare experimental and theoretical results;
- To summarise the obtained results and draw conclusions.

The Methodology of the Research

Experimental methods:

- "Classical" tensile and four point bending tests;
- X-ray microtomography with Skyscan 1172.

Numerical methods and computer programs:

- Mathcad, MatLab
- FEM software — SolidWorks

The Thesis Statements to Be Defended

1. Methodology for the prediction of elastic moduli of reinforced polymer matrix composites of unidirectional plain knitted fabric;
2. Models of knitted reinforced composites with elliptical and partly elliptical yarn cross-sections;

3. Strength modelling approach for polymer matrix and cementitious matrix composites with knitted reinforcement;
4. Usage of plain knitted fabric for concrete and fibre concrete reinforcing;
5. X-ray microtomography usage for determining geometrical properties of real knitted fabric and reinforcement in polymer composites.

Scientific Novelty of the Research

1. Modelling of mechanical properties of knitted fabric reinforced composites using non-specific widely used software;
2. Knitted fabric usage for fibre concrete reinforcing;
3. Strength modelling approach;
4. Determination of real knitted fabric geometry with X-ray microtomography technique.

Practical Value of the Research

Analysed type of reinforcement — knitted fabric — can be effectively used in detail with complex three-dimensional shape — shells, domes etc. Using the described modelling technology it is possible to predict mechanical properties (namely elastic moduli and strength) of composites reinforced by knitted fabric. It is shown than plain knitted fabric improves load capability of fibre concrete blocks.

Approbation of the Research Results

The main results of the Doctoral Thesis are presented in the following international scientific conferences:

1. Kononova O., Krasnikovs A., Kharkova G., Zalesky J., Machanovsky E. Mechanical Properties Characterization by Inverse Technique for Composite Reinforced by Knitted Fabric. Part 1. Material modelling and direct experimental mechanical property evaluation. 10^{th} International Conference "Vibroengineering — 2011", Kaunas, Lithuania, 13–14 October 2011.
2. Krasnikovs A., Kononova O., Kharkova G., Zaharevsky V., Akishin P., Ruchevskis S. Mechanical Properties Characterization for Composite Reinforced by Knitted Fabric Using Inverse Technique. Part 2. Mechanical property experimental evaluation by eigen frequency method. 10^{th} International Conference "Vibroengineering — 2011", Kaunas, Lithuania, 13–14 October 2011.
3. Krasnikovs A., Kononova O., Harjkova G., Mačanovskis E. Telpiski stiegroti kompozīti. „RTU 52. starptautiskā zinātniskā konference", Rīgā, 2011. gada 13. oktobrī.
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7. Krasnikovs A., V. Lapsa, V. Lusis, V. Zaharevsky, E. Machanovsky, and G. Harjkova. Mechanical Properties of a Layered Fibreconcrete Structure. "Mechanics of Composite Materials (MCM)", 28 May — 1 June 2012, Riga, Latvia.

8. Krasnikovs A., Kononova O., Harjkova G., Zaharevskis V. and Galushchak A. Mechanical Properties Characterization by Inverse Technique for Composite Reinforced by Knitted Fabric. "15^{th} European Conference on Composite Materials (ECCM-15)", 24–28 June 2012, Venice.
9. Harjkova G., Barburski M., Lomov S., Kononova O. Micro-CT Analysis of Glass Knitted Fabric Structure. 12^{th} International Scientific Conference "Engineering for Rural Development", Latvia, Jelgava, 23–24 May 2013.
10. Harjkova G., Lusis V., Akishins P., Krasnikovs A., Kononova O. Finite Element Analysis of Weft Knitted Composites. 4^{th} International Conference "Civil Engineering'13", Latvia, Jelgava, 16–17 May 2013.
11. Harjkova G., Barburski M., Lomov S., Kononova O., Verpoest, I. Analysis of Knitted Fabric Geometrical Parameters Using X-ray Microtomography. The 13^{th} AUTEX World Textile Conference 2013, Germany, Dresden, 22–24 May 2013.
12. Harjkova G., Barburski M., Lomov S., Verpoest I., Kononova O. Micro-CT based Geometry Recognition of Glass Knitted Fabric Reinforced Polymer Laminates. TexComp-11, Leuven, Belgium, 19 September 2013.
13. Harjkova G., Lusis V., Krasnikovs A. Experimental Investigation of Weft Knitted Fabric Layered Reinforcement Efficiency in Fibreconcrete. International Conference "Innovative Materials, Structures and Technologies", Riga, Latvia, 8 November, 2013.
14. Harjkova G., Kononova O. Analysis of Knitted Composite Reinforcement with Variable Cross-section shape. 18^{th} International Conference "Mechanics of Composite Materials", Riga, Latvia, 2–6 June 2014.

List of Publications

Publications in scientific journals:

1. Harjkova, G., Barburski, M., Lomov, S., Kononova, O., Verpoest, I. Weft Knitted Loop Geometry of Glass and Steel Fibre Fabrics Measured with X-Ray Micro-Computer Tomography. Textile Research Journal, 2014, Vol. 84, Iss. 5, pp. 500–512. ISSN 0040-5175. e-ISSN 1746-7748. Available at: doi:10.1177/0040517513503730.
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3. Kononova, O., Krasnikovs, A., Dzelzitis, K., Harjkova, G., Vagele, A., Eiduks, M. Modelling and Experimental Verification of Mechanical Properties of Cotton Knitted Fabric Composites. Estonian Journal of Engineering, 2011, Vol. 17, Iss. 1, pp. 39–50. e-ISSN 1736-7522. ISSN 1736-6038. Available at: doi:10.3176/eng.2011.1.05.

Publications in the full-text conference proceedings:

1. Harjkova, G., Lusis, V., Krasnikovs, A. Experimental Investigation of Weft Knitted Fabric Layered Reinforcement Efficiency in Fibreconcrete. In: Innovative Materials, Structures and Technologies, Latvia, Riga, 8 November 2013. Riga: 2014, pp. 59–63. e-ISBN 978-9934-10-584-5. Available at: doi:10.7250/iscconstrs.2014.10
2. Kononova, O., Krasnikovs, A., Harjkova, G., Lusis, V. Numerical Simulation of Mechanical Properties for Composite Reinforced by Knitted Fabric. In: Ebook Congreso Mundial TOMO IV, Spain, Barcelona, 20–25 July 2014. Barcelona, Spain: 2014, pp. 2925–2932. ISBN 978-84-942844-7-2.

3. Harjkova, G., Barburski, M., Lomov, S., Kononova, O. Micro-CT Analysis of Glass Knitted Fabric Structure. In: Proceedings of 12th International Scientific Conference "Engineering for Rural Development", Latvia, Jelgava, 23–24 May 2013. Jelgava: 2013, pp. 223–227. ISSN 1691-5976.
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7. Harjkova, G., Akishins, P., Kononova, O. Finite Element Analysis of Weft Knitted Composites. In: Civil Engineering '13: 4th International Scientific Conference: Proceedings. Vol. 4, Part 1, Latvia, Jelgava, 16–17 May 2013. Jelgava: 2013, pp. 82–85. ISSN 2255-7776. e-ISSN 2255-8861.
8. Vagele, A., Kononova, O., Krasnikovs, A., Harjkova, G., Polukoshko, S. Нелинейное моделирование вытаскивания волокна при разрушении фибробетона. In: Международная школа молодых ученых "Нелинейная динамика машин" (School-NDM). XVII симпозиум "Динамика виброударных (сильно нелинейных) систем" (DYVIS-2012): сборник трудов, Russia, Moscow, 20–26 May 2012. Moscow: ОНТИПиВ ИМАШ РАН, 2012, pp. 39–42. ISBN 9785904282035.
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10. Krasnikovs, A., Kononova, O., Harjkova, G., Zaļeskis, J., Lusis, V., Zaharevskis, V., Ruchevskis, S. Mechanical Properties Characterization of Composites Reinforced by Knitted Fabrics. In: 15th International Conference on Experimental Mechanics: Conference Proceedings, Portugal, Porto, 22–27 July 2012. Porto: Institute of Mechanical Engineering and Industrial Management (INEGI), 2012, pp. 1–17. ISBN 9789728826253.
11. Harjkova, G., Kononova, O., Krasnikovs, A., Eiduks, M., Machanovskis, E., Dzelzitis, K. Elastic Properties of Cotton Fabric Based Polymer Composites. In: 10th International Scientific Conference "Engineering for Rural Development": Proceedings, Latvia, Jelgava, 26–27 May 2011. Jelgava: Latvia University of Agriculture. Faculty of Engineering, 2011, pp. 402–407. ISSN 1691-5976.
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13. Kononova, O., Krasnikovs, A., Dzelzitis, K., Eiduks, M., Harjkova, G., Vagele, A. Mechanical Properties of Composites Reinforced by Cotton Knitted Fabric. In: Proceedings of 7th International DAAAM Baltic Conference "Industrial Engineering", Estonia, Tallinn, 20–23 April 2010. Tallinn: Tallinn University of Technology, 2010, pp. 423–429. ISBN 9789985599822.

14. Harjkova, G., Barburski, M., Lomov, S., Verpoest, I., Kononova, O. Micro-CT based Geometry Recognition of Glass Knitted Fabric Reinforced Polymer Laminates. In: TexComp-11 Conference Proceedings, Belgium, Leuven, 19–20 September 2013. Leuven, Belgium: 2013, pp. 1–5.

Patent:

Latvian patent: 14679 METHOD FOR REINFORCING CONCRETE AND FIBRECONCRETE CONSTRUCTIONS. Authors: Galina Harjkova, Vitalijs Lusis, Olga Kononova, Andrejs Krasnikovs

The Volume and Structure of the Doctoral Thesis

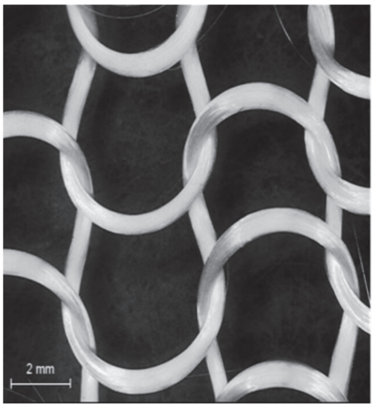
The volume of the Doctoral Thesis is 160 pages. It consists of the introduction, four chapters, conclusions, list of references and four appendices.

DESCRIPTION OF THE CHAPTERS OF DOCTORAL THESIS

Chapter 1. In this chapter the overview of literature is given. Main interest is devoted to the analysis of properties and specifics of knitted fabric reinforced composites, description of knitted structure types and models, as well as to the overview of experimental techniques and possible applications. Knitted fabric geometrical models [13], [14], [19], [21] are explored as well as composite modelling approaches.

Although plain knitted reinforced composites have been observed by many researchers [2]–[10], [15]–[18], [24] and many different theoretical models exist (for example, [5], [6], [23]) the lack of a comprehensive understanding of the way knitted composites behave still acts as an impediment to the wider acceptance of the material and, hence, expanded application [12]. Assumption about yarn circular cross-sections used in most models is relatively unrealistic, since yarns are easily compressible by the lateral forces acting in the interaction areas. This assumption cannot be used for the fabric subjected to a tensile load, since the compression forces increase dramatically in the extended fabric, and this leads to considerable displacement arising from the mutual compression of yarns [16]. We can conclude that there are no generalised model of knitted reinforcement and no evaluation of existing models using FEM programs as well as there is lack of comprehensive comparison of experimental, analytical (simulation) results. Usage of weft-knitted fabric for concrete and fibre concrete reinforcing is almost unexplored.

Chapter 2 is devoted to experimental study; in this chapter manufacturing of samples is described together with two experimental testing methods — tensile tests that are one of the classical research methods and X-ray microtomography (micro-CT) that is a relatively new nondestructive research method for determining material inner structure. Tomography usage in materials science has a large potential, because this technique allows making the spatial analysis of internal structure that is not possible by standard microscopy techniques. Unlike SEM (Scanning Electron Microscope) or light microscopy based on periodic cuts, microtomography does not require preparing sample serial cross-sections. Micro-CT has not been widely used in research of knitted reinforcement structure yet.



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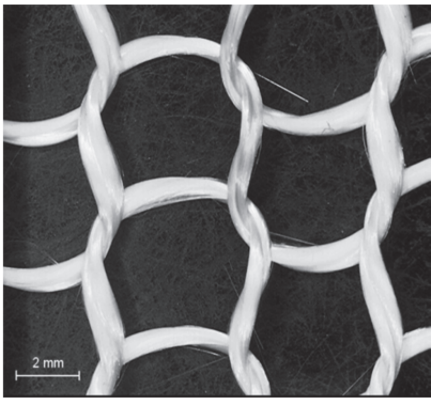

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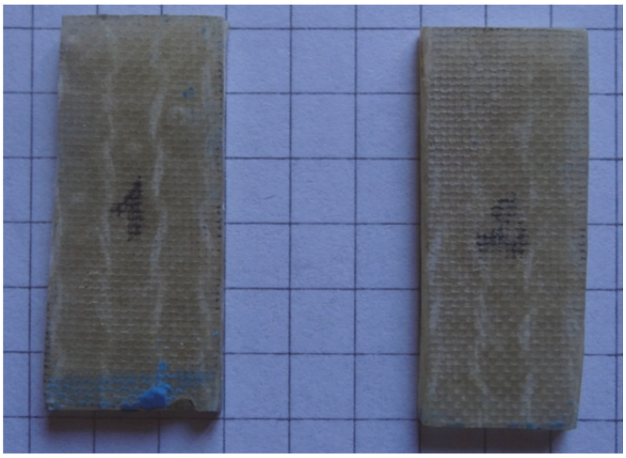

(c)

Fig. 1. Samples for microtomography analysis: fabric G2 (a), G3 (b) and 4-ply composite (c).

Chapter 2 describes the analytical analysis procedure for determining geometry of real plain knitted fabric. In this study X-ray microtomography is used for obtaining geometrical parameters and 3D visualisation of a loop. Two kinds of glass fibre knitted fabric and 4-ply composite material are used as samples. It has been demonstrated that this method is a suitable tool for determination of textile reinforcement structure. Extracted geometry can be used for further research, for example, for FEM analysis.

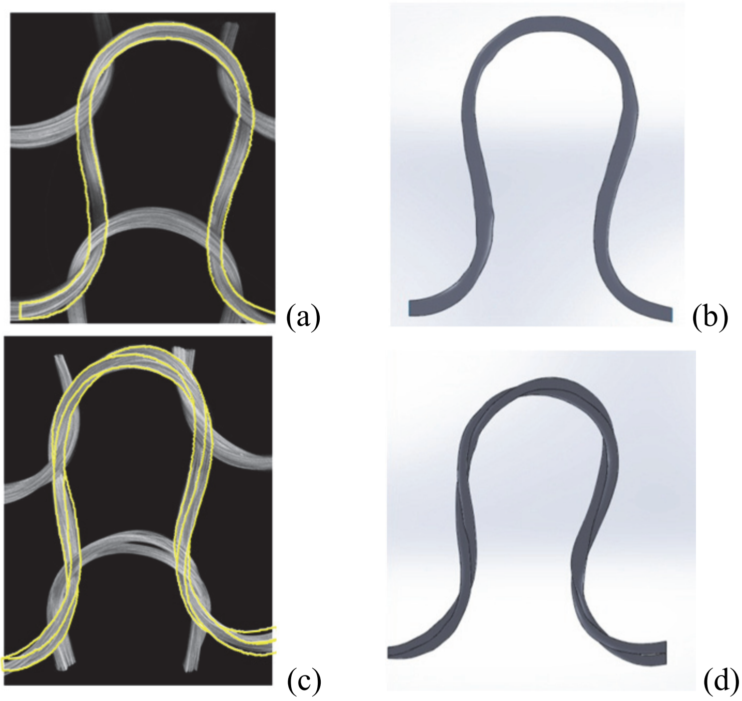


Fig. 2. Visual results of microtomography analysis for fabric G2 (a, b) and fabric G3 (c, d): (a), (c) reconstructed picture of fabric, (b), (d) geometrical model of one loop.

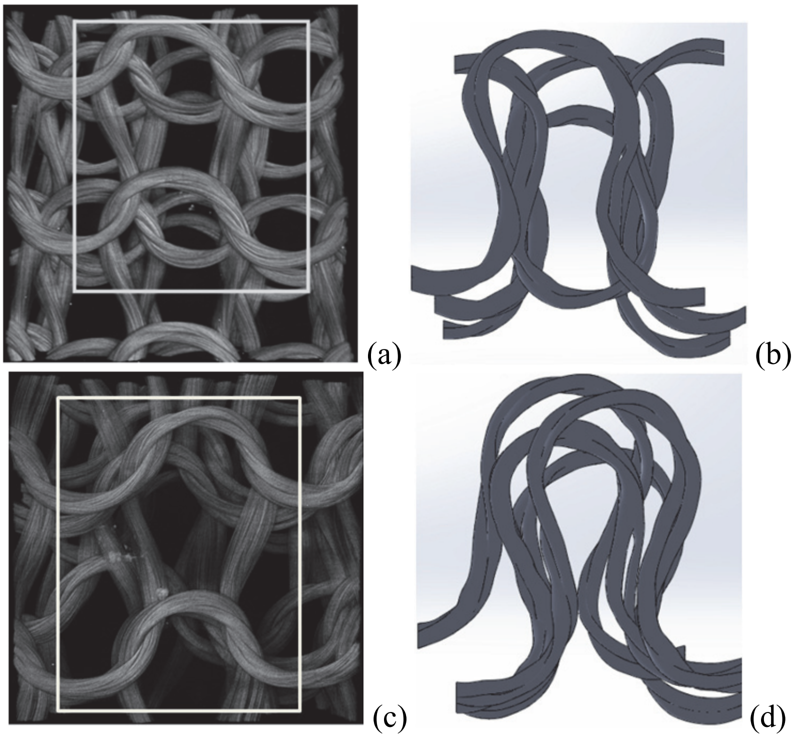


Fig. 3. Knitted fabric reinforced composite material: — Sample 1 (a–b) and Sample 2 (c–d): (a), (c) reconstructed volume; (b), (d) geometrical model based on measured data.

Analysing results of the study it can be concluded that:

- Standard microtomography equipment can be used for determining geometry of fibrous structures;
- Using this technique it is possible to define areas and shapes of yarn cross-sections that can improve existing models, especially in those, where yarn cross-sections are assumed to be circular;
- Areas of cross-sections as well as ellipticity vary depending on yarn region: in two yarn contact (crossover) zones, cross-sections are more elliptical and have smaller areas, which reflect the yarn compression in the contact zones;
- The yarn middle line obtained from micro-CT data agrees well with the Leaf-Glaskin theoretical model; divergences are observed in the loop legs.

From tensile test mechanical properties (namely elastic moduli in two principal material directions) are obtained for single ply and 4-ply composite material. During the experiments stress-strain curves were recorded (4., 5. att.). These curves were used for calculating moduli of elasticity at 0° and 90° directions. The obtained moduli are: for 4-ply KM — E_L = 5.46 GPa, E_T = 3.95 GPa, for single ply composite — E_L = 1.545GPa, E_T = 1.543 GPa.

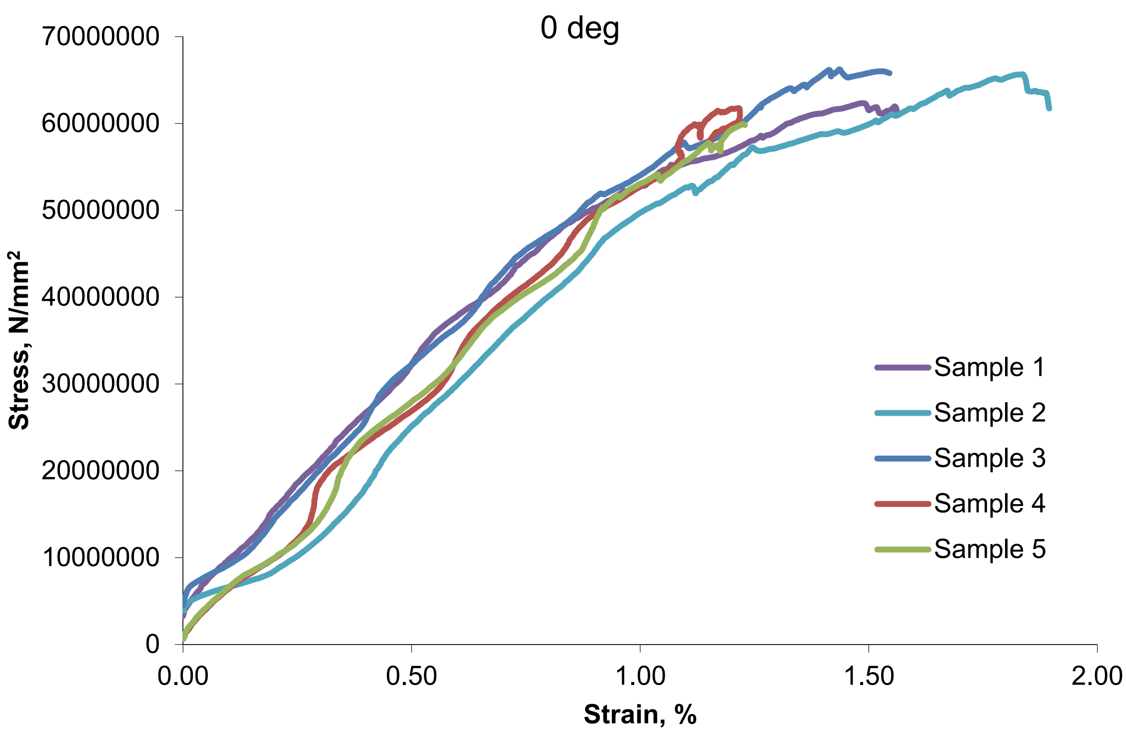


Fig. 4. Experimental results for 4-ply 0º samples.

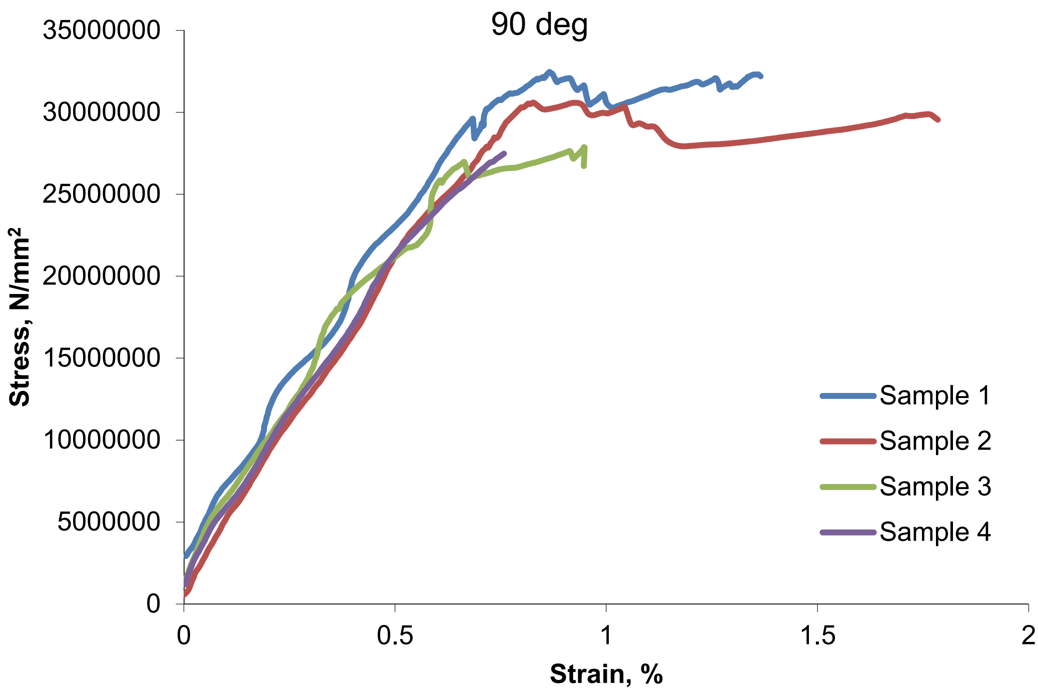


Fig. 5. Experimental results for 4-ply 90º samples.

Chapter 3. In the chapter, the theoretical study on polymer plain knitted fabric reinforced composite is described. The study can be divided into three parts: the first one is numerical modelling for determining Young's moduli, the second one is simulating of mechanical behaviour with FEM — models with circular, partly elliptical and fully elliptical yarn cross-sections are observed, the third one is numerical modelling of strength. The obtained elastic properties are compared with each other and with experimental data obtained in the previous chapter.

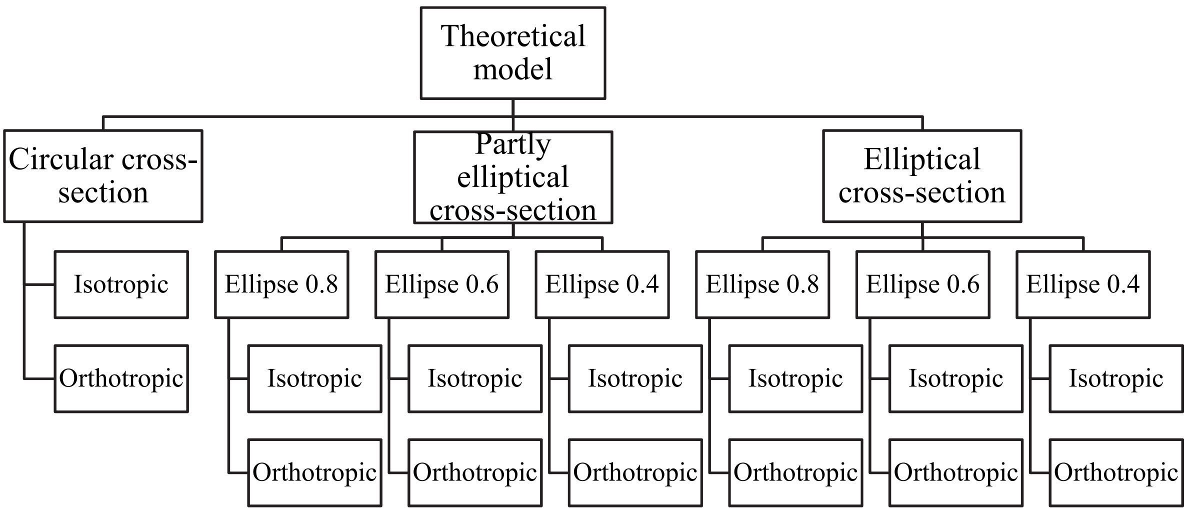
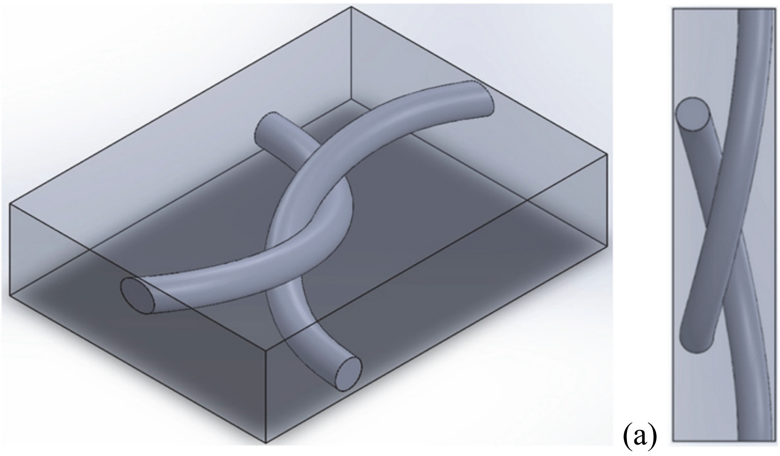


Fig. 6. FE models' overview.


(a)

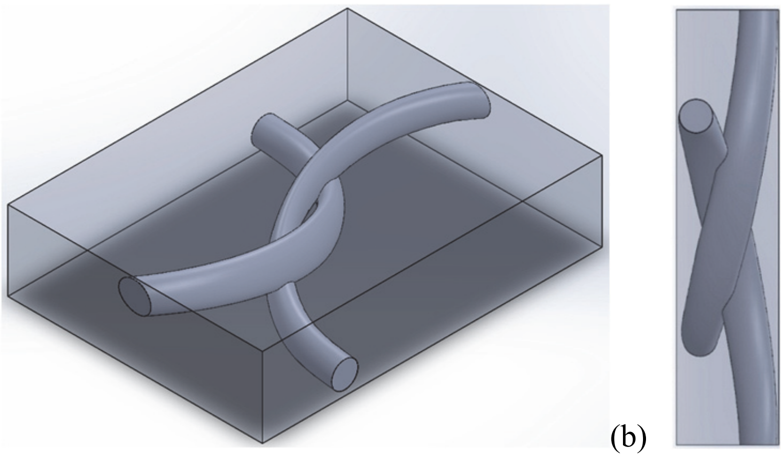

(b)

Fig. 7. Some models in an isometric view and a view from the left side: a — isotropic model with circular cross-section, b — isotropic model with partly elliptical (ellipse axis ratio is 0.4) cross-section.

Young's moduli are calculated dividing average stress by average strain.

Comparing the experimental (from tensile tests) moduli of elasticity with theoretical values (obtained from GEM and numerical modelling), we can conclude that the experimental values of the moduli of elasticity values coincide well with numerical modelling. Longitudinal moduli of some FE models fit well with experimental and theoretical data, while E_T modulus is bigger than the calculated and experimental ones; the values of transverse moduli are similar to E_L values. For some models, location of maximum stress was found using Matlab software.

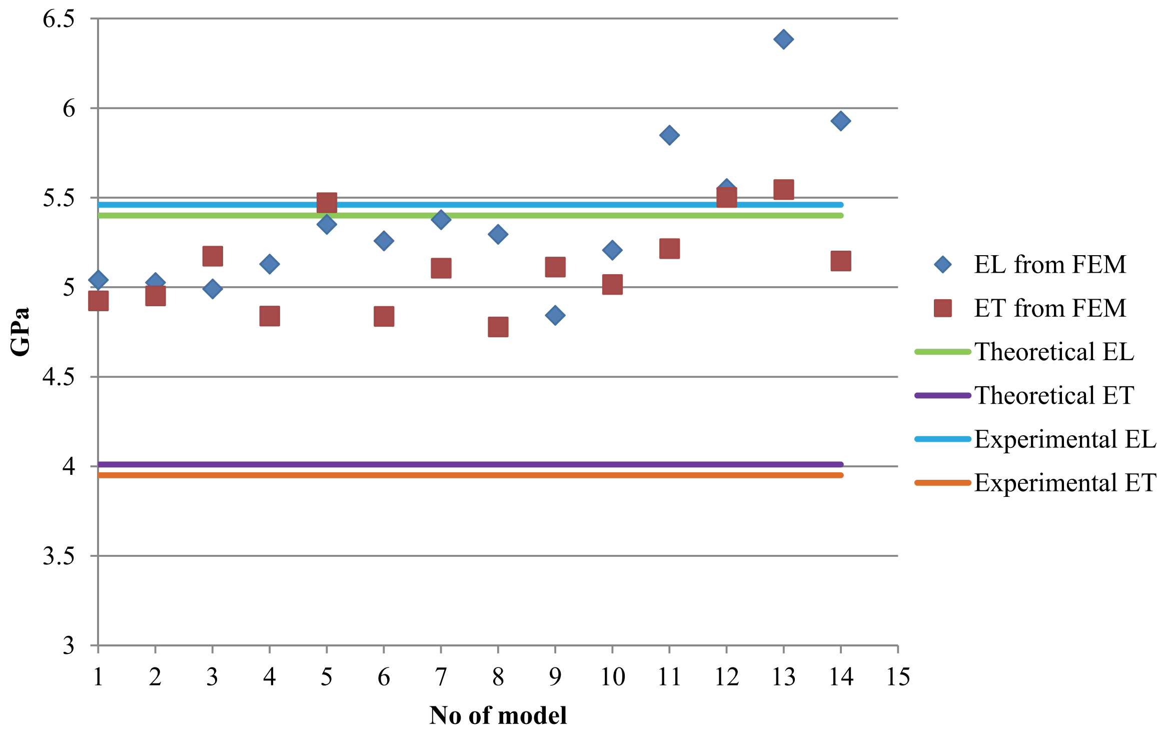
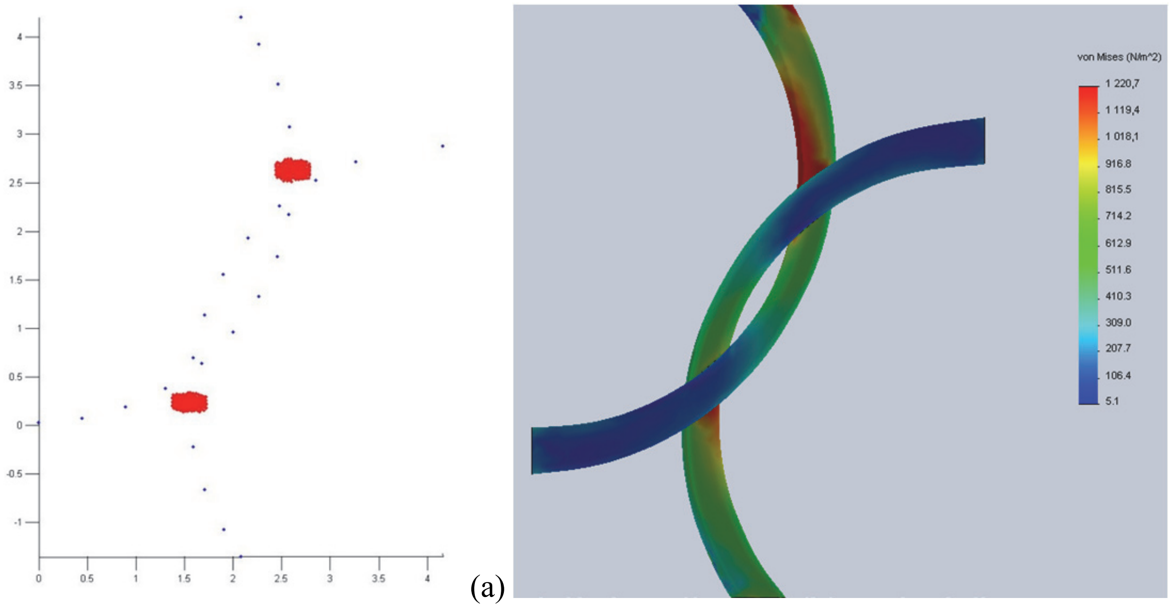


Fig. 8. Comparison of elastic moduli.



(a) (b)

Fig. 9. Location of maximum stresses for model No. 7 — isotropic model with partly elliptical (axis ratio is 0.4) cross-section (a) and stress distribution in the respective FE model.

In the third chapter, strength modelling with FEM is also carried out. Failure is observed as sequential yarn rupture in material under increasing external tensile load. Polymer plate reinforced by one-ply knitted fabric is observed. Plate is stretched by external loads that results in uneven stress distribution. Fabric one yarn will fail in place where stress has the maximum value.

Chapter 4 is devoted to usage of knitted fabric for fibre concrete reinforcing. Reinforcing of cementitious composites with continuous fibres is one of the effective ways to improve material load capability [22]. Cementitious composites can be reinforced with fibres of different geometry and made of variety of materials — steel, glass, synthetics or natural fibres [1] and textiles. Fibre reinforcement becomes effective mainly after a matrix is cracked and fibres keep the cracks (Fig. 10), thus improving the load carrying capability of the material. In the present research, fibre concrete samples are reinforced with glass fibre plain knitted fabric. The aim of the study is to evaluate influence of such kind of materials on fibre concrete properties. In Chapter 4 modelling is conducted as well. As a result of modelling, stress distribution has been obtained and 105 cross-sections have been analysed in order to define average stresses in each cross-section.

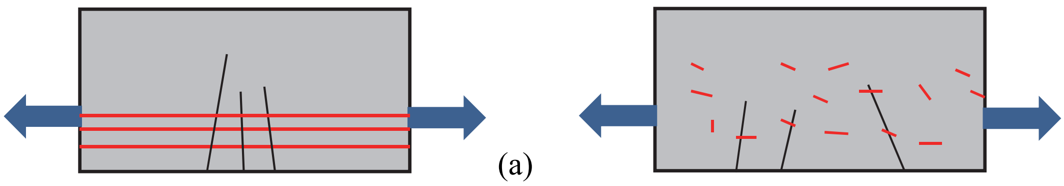

(a) (b)

Fig. 10. Fabric (a) and short fibre (b) reinforcement under tensile load in concrete (two different load bearing mechanisms) [11].

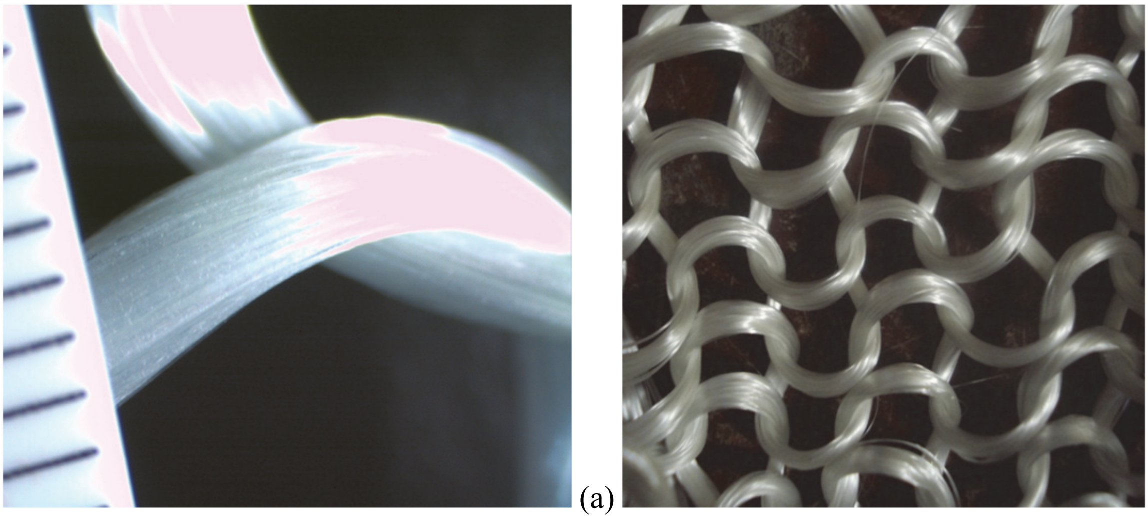

(a) (b)

Fig. 11. Knitted fabric reinforcement: (a) yarn intersection and fragment of fabric (b).

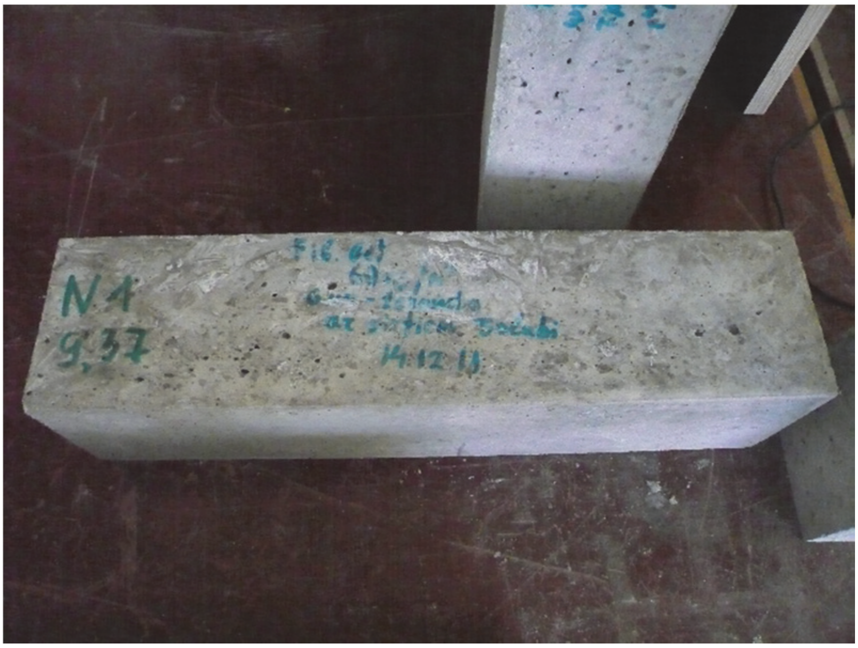


Fig. 12. Fibre concrete sample (100 × 100 × 400 mm).

Fibre concrete samples have been experimentally tested using 4-point bending tests. Influence of fabric reinforcement is shown in Fig. 13. The load-bearing capacity of the samples is 38–48 kN. Samples with knitted reinforcement (No. 1–4 in Fig. 13) have approximately twice bigger flexural load than non-reinforced samples (No. 5–6).

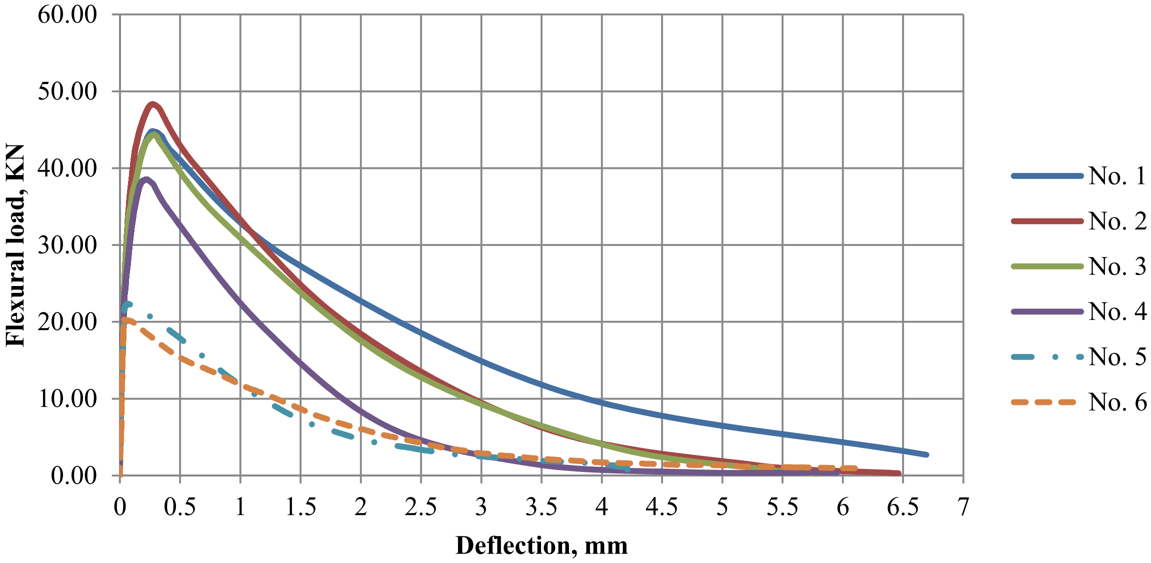


Fig. 13. Flexural load/deflection curves: samples No. 5 and No. 6 are without knitted reinforcement.

Analysing the results of the study it can be concluded that the concrete and fibre concrete can be successfully reinforced with a plain knitted fabric made from glass fibre yarns. Experiments showed improvement of flexural load.

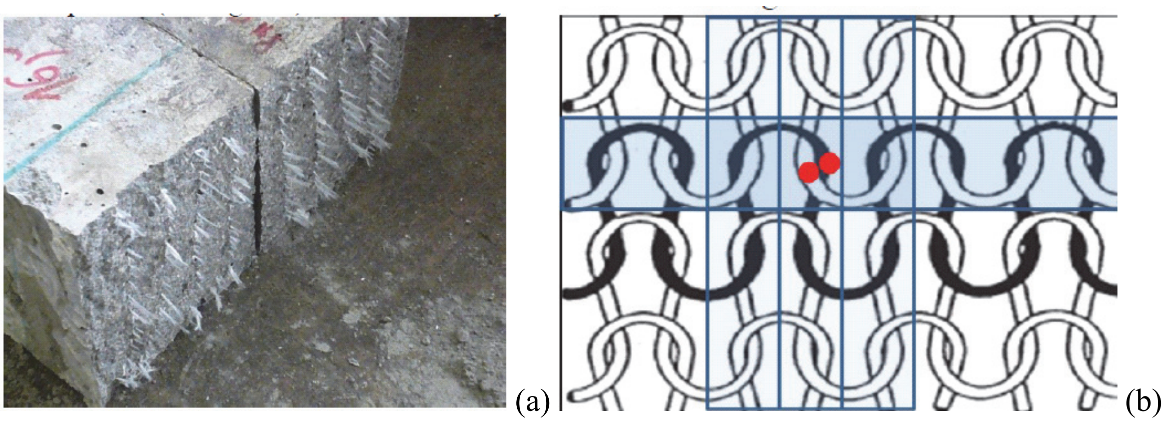


Fig. 14. (a) Concrete samples with 4-ply knitted reinforcement after fracture; (b) yarns under tensile load in macro-crack.

In order to simulate strength of the concrete blocks with knitted reinforcement, the structural model with probabilistic approach usage has been created and modelling of sequential fracture process of yarns is offered in this chapter.

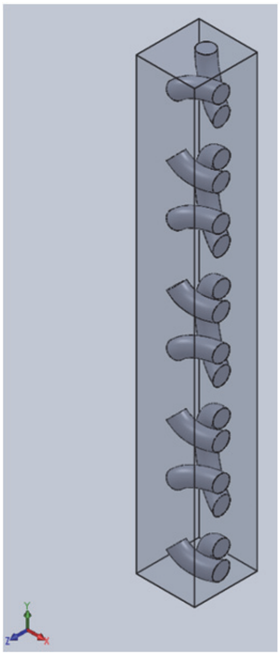
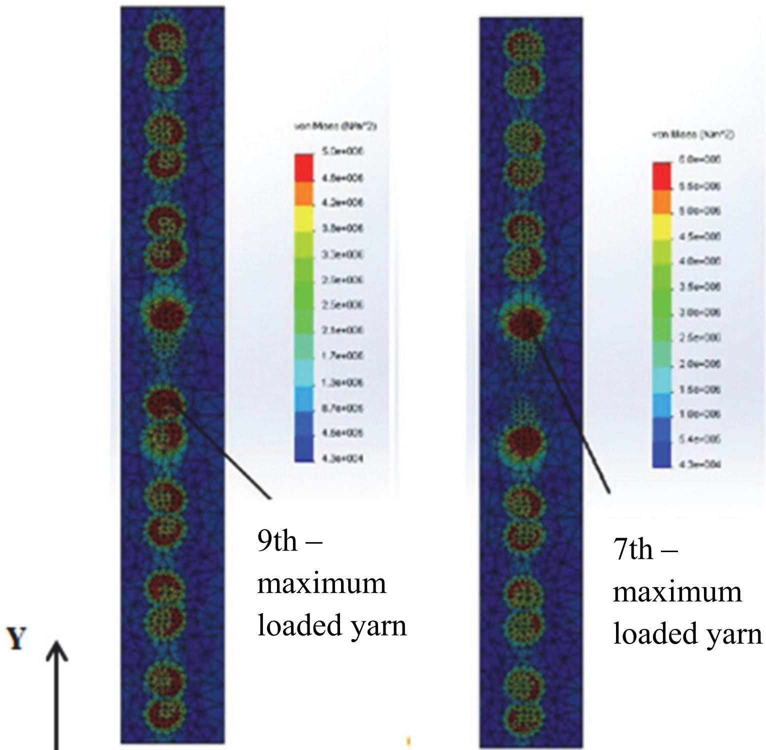


Fig. 15. Structural model used for strength prediction.



(a) (b)

Fig. 16. Von Mises stress distribution example: (a) one yarn is broken (8^{th} from the top), (b) two yarns are broken (8^{th} and 9^{th}).

CONCLUSIONS

In the present Doctoral Thesis composites with knitted fabric reinforcement have been observed. Usage of plain weft-knitted fabric for polymer and fibre concrete composites has been analysed. The following **studies** have been conducted:

- Tensile tests — Young's moduli in two material principal directions have been obtained for one-ply and 4-ply composites;
- Computer modelling using FEM in order to define mechanical properties of laminate; in models different cross-section types have been used;
- Numerical modelling of elastic moduli using the Bridging Matrix model;
- Determination of real geometry of knitted fabric using X-ray microtomography technique;
- Computer modelling with FEM to predict strength of knitted reinforcement composites;
- Experimental evaluation of knitted reinforcement influence on the load capability of fibre concrete samples.

Experimentally and theoretically obtained values of elastic moduli have been compared; realistic determination of the geometry of knitted fabric with microtomography technique has been offered; the strength modeling method of knitted reinforcement composite has been described.

The following **conclusions** have been made:

1. After literature review, it has been concluded that although many studies on knitted fabric reinforced composites are conducted, there is still a lack of comprehensive modeling approach, there is not enough evaluation of models in software based on FEM, strength prediction is almost not studied.
2. Microtomography technique can be successfully applied for obtaining structural properties of knitted fabric that can improve existing models. Currently using this type of analysis can be time-consuming, but it has a great potential, especially if there is a possibility to automate the processing of data and simplify data migration to 3D modelling programs.
3. As a result of tensile tests, elastic moduli in two material principal directions are obtained for one-ply and 4-ply plain weft-knitted fabric polymer composites. Young's moduli for one-ply material are similar.
4. Composites with knitted fabric reinforcement can be simulated in modern non-specific FE modelling program. In the present research, SolidWorks has been used. The obtained results for longitudinal moduli agree well with experimental and theoretical data; transverse moduli show a greater difference. It should be noted that SolidWorks is very sensitive to boundary conditions and change in mesh parameters.
5. In this study, composite strength has been modelled using FEM and probability theory.
6. Plain weft-knitted fabric can be successfully used for concrete and fibre concrete reinforcing in order to improve bearing power. The most rational way is to use this type of reinforcement in spatial components and 3D structures, such as shells.

Proposals for further research

On the basis of the research findings, the following proposals have been developed:

1. Carrying out more experiments for determining the moduli of elasticity, especially for laminates with different orientation angles of plies;

2. Optimizing and improving a finite element model for predicting elasticity moduli and strength/fracture properties; making validation of the parameter (such as boundary conditions, networking) influence on model properties; probably automated creation of models;
3. Deeply exploring the evolution of textile geometry under deformation process and effects of deformation geometry on material properties;
4. Making more accurate strength prediction;
5. Accomplishing the mechanical analysis of microtomography data (i.e., derived geometric model);
6. In order to use the opportunities provided by a microtomography technique, it is necessary to conduct a number of studies to improve the processing of output data; solution that would allow converting raw data after microtomographic scan directly to geometrical model in FEM software has a great potential.

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