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NUMERICAL SIMULATION OF MECHANICAL PROPERTIES FOR COMPOSITE REINFORCED BY KNITTED FABRIC

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Abstract. Composites reinforced by knitted fabric are materials with high potential in aerospace, machine building and civil engineering industries. In the same time such materials are mechanically non-linear with a high dynamic energy absorption possibility. Precise mechanical properties prediction has the great importance for such material use in the novel structures. Elastic properties of such material was calculated using structural modeling based on reinforcement and matrix mechanical and geometrical properties and FEM calculations. Structural failure model was elaborated for composite plate reinforced by multilayered knitted fabric. Probabilistic approach was used and was compared with elaborated deterministic structural model predictions. Numerical simulations results were compared with experimental data and comparison results were discussed.

1 INTRODUCTION

Polymer and brittle (concrete, ceramics) matrix composites, reinforced by knitted fabric are exhibiting attractive mechanical properties including high energy absorption and impact resistance. In woven fabric, threads traditionally are running horizontally and vertically. Contrary, in the case of knitted fabric, strands are forming loops. A knitted fabric is highly deformable in all directions. Depending on fibers are used, some of them are more deformable than others. The reason is – yarns are not making any straight line anywhere in the knitted fabric. Looking at the figure 1(a) is easily to recognize possible motions in the fabric – threads sliding, loops twisting, bending and stretching leading to technological advantage – excellent deformability, shape forming ability and flexibility, which allows it to be used in any complex shape mould without folds. Mechanical properties of weft knitted fabric are established by mechanical properties of the fibers are included in the yarn as well as yarn's thickness and its degree of twist, size of the loops in the fabric and by chemical and mechanical treatments were applied to the yarn [1,2]. Fabric structural deformation modes can be recognized through the interaction of structured yarns within the fabric. Yarn span bending or straightening occurs when the two threads are belonging to a two adjacent loops, are stretching in opposite directions. It is one of most important mode in knitted fabrics according to the knit loop geometry. Straightening also can be found in woven and braided fabrics. Inside-yarn slip is possible in the loop straight part during fabric stretching as well as it is coupling with yarn bending in the more curved loop part. In the last case the friction between the yarns becomes important. In this situation the matrix and fiber sizing usually lubricate the yarn to help this mode of deformation. Next is thread stretching in the longitudinal direction. This deformation mode is very important at fabric final deformation stage, when all geometrical (loops deformations) movements are hampered. Another deformation mechanism to consider is yarn twist, which has been observed in knitted fabrics and not so much in woven fabrics. Technologically the twist creates a resistance to the forming the looping structure of the knit. And in fabric deformation the twist creates a resistance to the increase in yarn curvature. Another deformation mechanism is a yarn transverse compression. This mode is realized where, forces at yarn cross-over points compress it and cause the yarn to flatten out and conform to the curvature of perpendicular yarns (if it is combined with bending). Finally, longitudinal compression of the yarn span is leading to its buckling. Buckling can be realized in a form of buckled cylindrical shape of the yarn as well as buckling in a form of “china flashlight”.

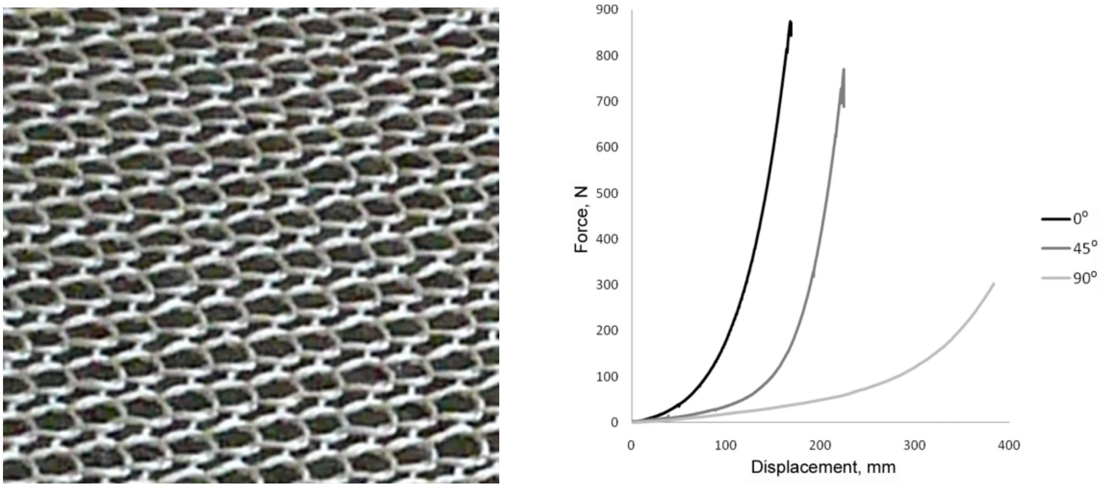

Figure 1: (a) Our made glass fiber knitted fabric’s structure; (b) Load-displacement curves for knitted fabric’s samples were cut under different angles (cotton).

2 YARNS MECHANICAL PROPERTIES

First were investigated natural fiber (cotton) yarns. The length of the investigated cotton yarn specimen was 50 m, specimen mass 1 g and obtained linear density 200 dtex or 20 tex, density of the cotton ρ = 1510 kg/m^3, diameter of the yarn was determined as $d = 1{,}3 \times 10^{-4}$ m. Elastic modulus was 3.68 GPa. After that, type E glass fiber yarns were experimentally investigated. Density of the glass fibers was ρ =2540 kg/m^3, diameter of the yarn d was equals 0.37x10^{-3} m. Linear density of the glass yarn was calculated and was equals to 275.6 tex.

Value of the elastic modulus for glass yarn was 73.4 GPa.

3 COMPOSITE MATERIAL MECHANICAL PROPERTIES (EXPERIMENTAL RESULTS)

Majority of the production processes used in the manufacture of ordinary fiber reinforced composites may be used and applied to textile composites. Main reason here is that in many cases manufacturers are looking at existing manufacturing methods and equipment. Thermoset matrix composite plates (5 layers, 2.2 x 10^{-3} m thick), reinforced by the cotton fabric, were manufactured using acrylic resin. Acrylic resin parameters: elastic modulus 3.3 GPa, density 1120 kg/m^3, Poisson's ratio 0.35. Thermoset matrix composite plates (4 layers, 2.1 × 10^{-3} m thick), reinforced by the glass fabric, were manufactured using epoxy resin. Epoxy resin parameters: elastic modulus 3.3 GPa, density 1360 kg/m^3, Poisson's ratio was 0.22. Rectangular specimens 25 × 250 mm were cut out of the plates for tensile tests under different directions to knitted fabric orientation (angles 0°, 45°, 90°).

Mechanical tests were performed on composites with fiber weight fraction 27% for cotton fabric and 11% for glass fabric. Knitted fabric samples were tested according to the preparation procedure described in ASTM D 5083-02. Tensile tests were executed on an electromechanical testing machine Zwick Z150. All tests with composite specimens were displacement-controlled with the loading rate of 5 mm/min. Load–displacement curves were recorded during the tests. Experimental data in real time regime were transferred to the PC. The stress–strain curves were obtained.

Concrete prisms 10cmx19cmx40cm reinforced by four glass fiber knitted fabrics were tested under four point bending till rupture (see figure 2 (a,b)). Applied load – prism midspan point vertical deflection curves were obtained. Simultaneously, elastic modulus of plain comcrete (without glass fiber fabrics) was measured using prepared cubes. Elastic modulus was 27.63 GPa.

Figure 3: (a) Concrete prism, reinforced by four layers of glass fiber knitted fabrics, under four point bending; (b) Macro-crack opening with glass fiber yarns failure during prism bending under the increasing load.

4 COMPOSITE MATERIAL ELASTIC PROPERTIES NUMERICAL SIMULATION

Was supposed that knitted fabric composite consist of multiple plain wefts knitted fabric laminas, each of which can be oriented under different angle to material common axe [3]. The 3D geometrical modeling of the knitted fabric was based on the Leaf and Glaskin model. A schematic diagram of an idealized plain weft-knitted fabric structure is shown in Fig. 3.

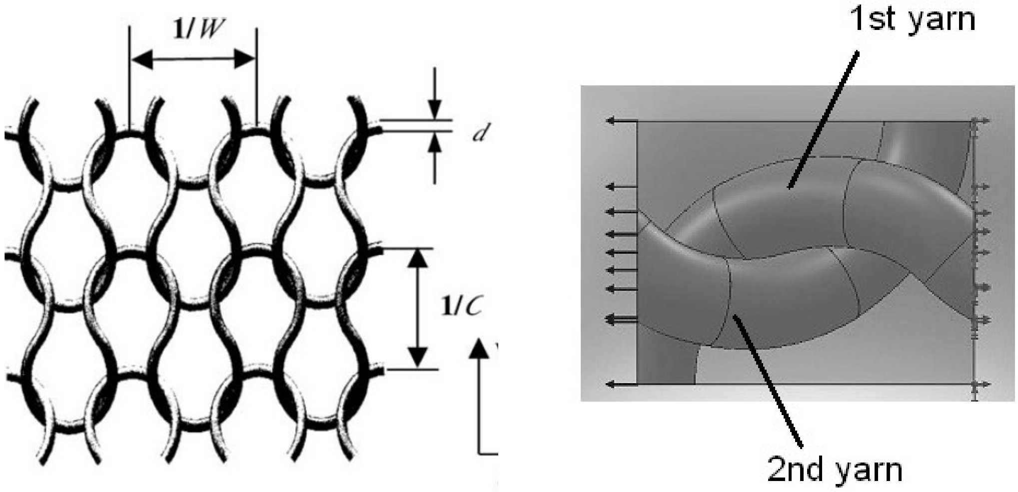

Figure 3: (a) Schematic diagrams of knitted fabric structure [3,4]; (b) Unit cell 3D model, used in our calculations for cotton knitted fabric (side view).

According to Leaf and Glaskin model [3], the fabric's structural geometry is completely defined if three geometric parameters, the wale number, W the course number C and the yarn diameter d are provided. The wale number is defined as the step of loops of the fabric per unit length along width (in the course) direction, whereas the course number is defined as the step along the length (in the wale) direction, as indicated in Fig. 3 [4]. Elastic properties of the composite material can be calculated using material's representative volume or unit cell (shown in Fig.3(b)). All numerical simulations were carried out for a 3D unit cell of the cotton and glass fabric composites [4].The visual unit cell model (geometry) of the weft-knitted fabric composite was created using CAD software. Numerical model (based on FEM) was created using Solid Works code. The yarn was considered as a homogeneous elastic rod and as elastic modulus of the yarn was used the experimentally obtained value, equal to 3.7 GPa for cotton yarn and 73.4 GPa for glass yarn, elastic modulus of the acrylic and epoxy resins were indicated earlier and were equal to 3.3 GPa. Similar procedure was repeated for concrete matrix. At first, coordinates, x y and z for the first and the second yarn were obtained [4]. The parameters of the considered cotton knitted fabric are the following: wale number W=13. loops/cm, course number C=20. loop/cm, yarn diameter d=0.013 cm. The parameters for glass knitted fabric are the following: wale number W =1.05 loops/cm, course number C= 2 loops/cm, yarn diameter d =0.037 cm. In Solid Works code was obtained 3D sketch, inputting x, y and z coordinates for both yarns after that they were connected by spline function. Yarn was simulated as homogeneous elastic rod by using sweep function that creates a base by moving a profile (diameter of yarn in our case) along a spline curve. The matrix of plain weft knitted fabric lamina was created as parallelepiped with holes for yarn by using sweep cut function. And at last was created assembly between yarns and matrix (see Fig. 3).

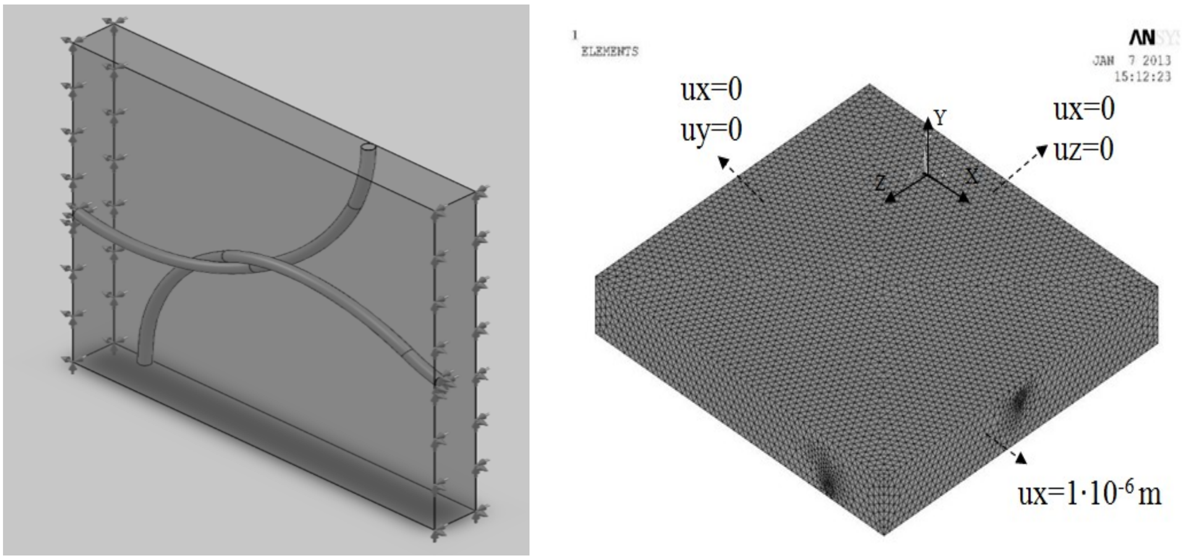

Figure 4: (a) Unit cell Solid Works 3D model, used in our calculations for glass knitted fabric (orientation 0°), 3D view; (b) Unit cell 3D mesh.

One butt-end surface of unit cell was fixed, to another butt-end surface was applied pressure loads, to side surfaces were applied symmetry conditions. Finite elements analysis was carried out for this elastic model (Fig. 4). Strain value was averaged over the butt-end surface, under applied loads and was calculated ratio between applied pressure and average strain values. Similarly were created unit cell models for another directions corresponding to reinforcement.

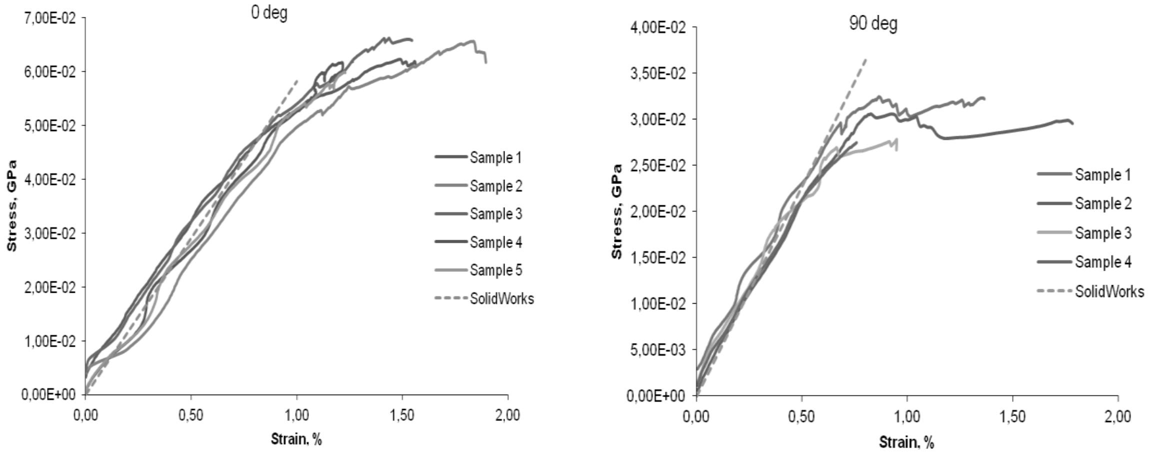

Figure 5: The stress-strain curve of glass knitted fabric composites a) at 0 deg; b) at 90 deg.

The elastic modulus was determined analyzing data with the maximum strain value of about 0.6%. This level was used expecting that damage will not develop in this relatively low (for our textile composite) strain region. The computer simulation data was compared with experimental results for samples cut under different directions and are shown in Fig. 5.

5 COMPOSITE MATERIAL STRENGTH NUMERICAL SIMULATION

Concrete matrix prisms, reinforced by four weft knitted fabrics, were subjected to four point bending. During increase of external load small micro-cracks in concrete are linked and grown leading to yarns stretching in potential macro-crack plane. This plane is crossing loops, within one single loops row (see figure 6 a, b). Yarns are stretching till one of them fails. After that is failing another yarn, and so on. This process is rapid and is accompanied by single fibers break in the yarn and loose ends pulling out of macro-crack sides (see fig. 6a). Similar failure picture can be observed in polymer matrix glass fiber composites subjected to unidirectional tension. For such process numerical simulation, stresses in yarns within one single loops row (see fig. 6 b).was numerically calculated using FEM.

Figure 6. (a) Concrete prism, reinforced by four glass fiber knitted fabrics after failure; (b) Stretched yarns row in the macro-crack.

Assembly of few unit cells within one row (row number *i* in figure 6 b) of the weft-knitted fabric composite was loaded by tension. One yarn fails. One butt-end surface of assembly of unit cells was fixed, to another butt-end surface was applied distributed on surface tensile load, to side surfaces were applied symmetry conditions. Finite elements analysis was carried out for this elastic model. After that was calculated situation when failed few yarns in the assembly. In every case most overloaded neighbor yarn was recognized and obtained overstress was fixed.

In figure 7 (a) is shown stress redistribution on yarns in the assembly, if one single yarn breaks (yarn number 8th from the top). The neighboring yarn (9th yarn from the top) is maximally loaded. Now 9th yarn fails. Overstresses on neighbors are shown in figure 7(b). The neighboring yarn (7th yarn from the top) is maximally loaded. 7th yarn fails and overstresses on neighbors are shown in figure 7(c). More overloaded is yarn number 10th. 10th yarn fails and overstresses on neighbors are shown in figure 7(d). After that overstresses were obtained on neighbors, if 5, 6,…14 adjacent yarns were failed. Overstresses on more overloaded yarns in vicinity of broken 12, 13, 14 and 15 yarns are shown in figure 8. Probabilistic modeling of damage accumulation in composite material, under an arbitrary external tensile load is based on the assumption, that failure is a complex stochastic process starting with scattered, isolated yarns brakes, overstress redistribution on adjacent to broken fibers, failure of overstressed neighbors, forming breaks clusters and the breaks clusters growth in the range of each fabric, single loops row. This process starting will transforms to

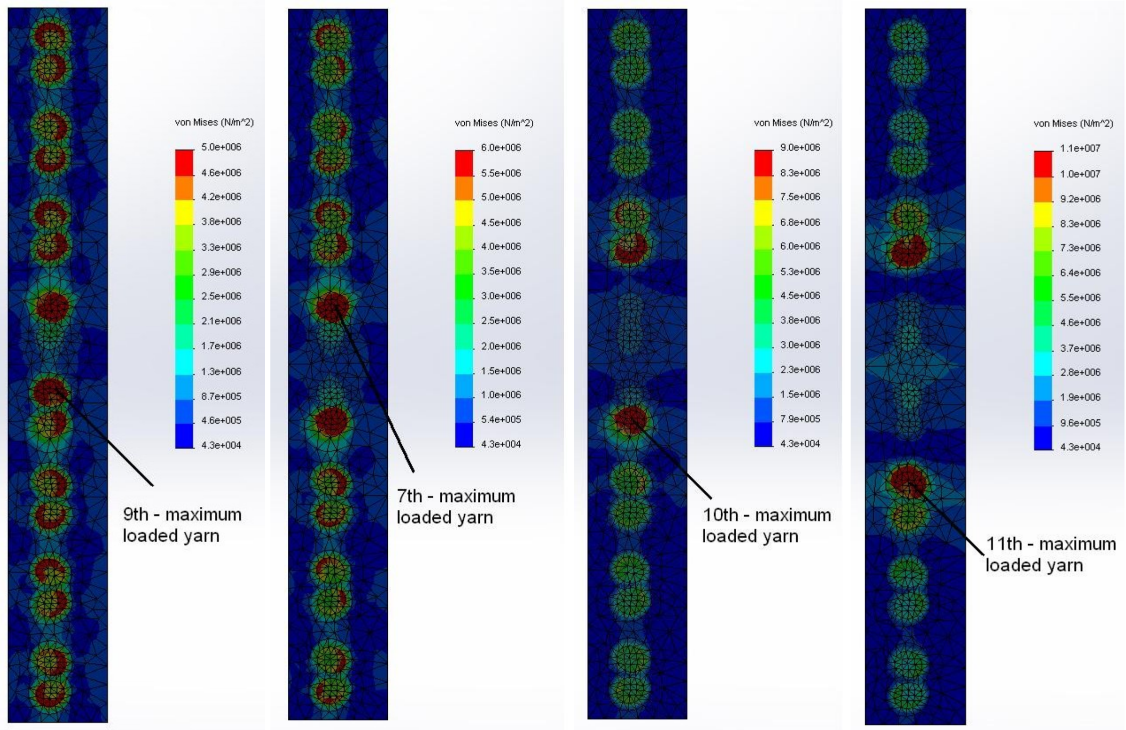

Figure 7. Overstresses on adjacent neighbors yarns if *n* yarns are broken. (a) one yarn is broken (eighth from the top); (b) two adjacent yarns are broken (eighth and ninth from the top); (c) three adjacent yarns are broken (seventh, eighth and ninth from the top); (d) four adjacent yarns are broken (seventh, eighth, ninth and tenth from the top). Are shown equivalent von Mises stresses.

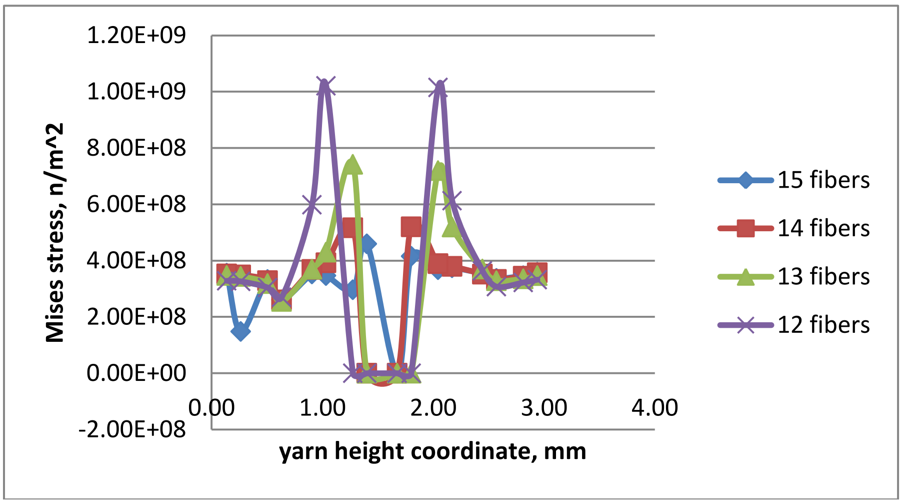

Figure 7. Yarns break progression. Equivalent von Mises stresses.

catastrophic ultimate cluster growth, when overstress distributed on closest unbroken neighbors will immediately initiate one of the next fiber break. Clusters interaction between two adjacent fabrics was ignored. Let introduce the random variable with probability function: To find probability of cluster formation, which was born and after that was reached at least size i of adjacent broken yarns (within one single loops row) is possible in different ways. Two of them were observed. As a single yarn break probability function was used Weibull distribution function. Sample break was associated as a formation of infinity large cluster in the sample.

6 CONCLUSIONS

Two different approaches were executed: a) structural modeling, including numerical FEM (Solid Works software was used) calculations, based on reinforcement and matrix mechanical and geometrical properties which were measured experimentally and b) direct experimental mechanical properties measurement approach with the goal to obtain in plane elastic properties of polymer composite reinforced by knitted fabric. Elastic results were obtained for two types of composite materials, reinforced by cotton and glass knitted fabrics. A geometrical–numerical (FEM) model was created with the goal to predict elastic properties of the knitted fabric layered composite. Model is structural with high potential of predicting. Structural probabilistic composite material failure model was created, based on overstress sequence in composite material having different number of ruptured yarns in it. Numerical simulation results were compared with experimental data showing high level of coincidence.

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