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ABSTRACT OF THE PhD THESIS

THEORETICAL AND EXPERIMENTAL RESEARCHES REGARDING THE MECHANICAL BEHAVIOUR OF THE COMPOSITE MATERIALS REINFORCED BY FABRICS

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1. INTRODUCTION

This Ph.D. thesis aims to present a study, from the point of view of the mechanical behaviour, of the composite materials that have as support polyamide PA 6.6 fabric, also known under the commercial name nylon, and on the influence of the material with which it is impregnated (silicone in most cases) on the mechanical properties of these materials. These composite materials are the materials that are the most often ones used for realising airbags for cars. Knowing the importance granted by car manufacturers to safety, the author considered as necessary to realise such a study regarding their mechanical behaviour, but also regarding the offering of new solution concerning materials that could be used in future. It is a known fact that airbag producers would like to replace silicon with other materials, so this Ph.D. thesis also studies the behaviour, from a mechanical point of view, of other nanocomposite materials that are also based on a polyamide PA 6.6 fabric but are obtained by means of the deposition of nanoparticles of various oxides on the fibres that make up the polyamide yarns. Also within the researches comprised in this thesis, it is sought to determine the influence of stress concentrators (various perforated holes) on the mechanical behaviour of the material of which the airbag is made. In order to show the mechanical behaviour of these composite materials, there were carried out tests not only on the coated or uncoated weaving materials, but also on the polyamide yarns of which the fabrics are made.

Nowadays, the employment of the computer in the design process is indispensable, so that it was possible to reduce the time between designing a car model and its physical realising to just 6 months as compared to 6 years as it was even at the end of the last century. Of course, within this process, the computer-aided drawing (CAD) activities are very important, the advantages of using such software packages being well-known. However, this must not diminish the importance of the other components that compose an integrated computer-aided design system and especially the importance of using numerical simulation software in the verification process.. The best known and at the same time the most used of the implemented numerical methods is the finite element method. If numerical simulation software packages managed a few years ago to allow the realising of only static simulations with a limited number of nodes, nowadays, thanks to the emergence of powerful computers with multi-core processors and with enough RAM memory, it is possible to run within a decent timeframe dynamic explicit analyses or implicit analyses that would allow the presentation of the behaviour in time not only from a mechanical point of view, but also from a thermal, electrical etc. point of view.

As mentioned, the car manufacturers now put more and more emphasis on safety and this is shown also through the usage, for crash studies, of these simulation software packages based on the finite element method. In all these studies it is necessary to also simulate the behaviour of the airbags. In order to obtain from these analyses results that are as close as possible to reality, it is necessary to precisely define the material properties and the behaviour of these materials.

The current thesis also aims at setting up a method that is efficient and as fast as possible, for determining the material data for airbags used in explicit dynamic simulations, an element that is currently of major importance. This method is based on the inverse analysis applied with the help of the finite element method.

2. THE STATE OF THE ART IN THE AREA OF COMPOSITE MATERIALS REINFORCED BY FABRICS. PHD THESIS OBJECTIVES

Chapter 2 presents the state of the art in the area of composite materials reinforced with fabrics. A first subchapter presents the types of materials that compose these composite materials. Then, in a separate subchapter there are presented the macro and meso forming modes of the fabric materials. The four modes for the forming at the macro level for fabric-reinforced composite materials are: transversal compression, plain tension, shear and bending. The macro level studies the strains while looking at the composite material as a whole. The meso level of forming exists due to the internal interaction of the fibres that compose the fabric. The eight forming modes at the meso level are: friction between yarns, shear between yarns, bending between yarns, yarn buckling, internal friction (between fibres), yarn tension, yarn compression and yarn torsion. Because the current Ph.D. thesis aims at studying composite materials reinforced by fabrics that are used for airbags, an important percentage of the discussion of the state of the art is dedicated to this type of product. After a short presentation of the history of airbags, there are reviewed the manufacturing technologies for these components that guarantee the safety of passengers in cars.

There are presented the technical requirements that the airbags need to meet: folding-unfolding capacity, resilience, resistance to high temperatures, low permeability for air, high resistance to dynamic loads, low weight of the fabric, high strength of the fabric, good abrasion resistance and stability at aging. In the following, the author presents a history of using polyamide yarns to realising airbags but also of using silicon as coating material. In a distinct subchapter there are presented the representative mechanical models for fabrics, namely the Pierce model and the

Kawabata model. Two distinct subchapters of the state of the art identify the main researches in the area of simulating by means of the finite element method the behaviour of the composite materials used for realising airbags and the main experimental researches for the same materials. The chapter dedicated to the state of the art ends with a subchapter that defines the objectives of the Ph.D. thesis.

Based on the analysis of the state of the art in the domain, the objectives of the Ph.D. thesis were determined as follows:

1. Synthetizing the information presented in the state of the art concerning the identification: of the types of fabrics used in realising airbags, of the mechanical properties and functional properties that these must fulfil in order to use them in manufacturing airbags and of the materials used in realising these fabrics;
2. Elaborating a theoretical study regarding the mechanical behaviour of fabrics used in realising airbags at the loads at which these are subjected conventionally during functioning: uniaxial tensile load, biaxial tensile load and shear load;
3. Three-dimensional geometrical modelling at mesoscopic level of several types of fabrics and the verification of their mechanical behaviour based on static numerical simulations using finite element methods for various types of stresses (uniaxial tensile load and biaxial tensile load);
4. Elaborating explicit dynamic numerical simulations for uniaxial tensile load and shear at macroscopic level for composite materials manufactured by impregnating fabrics;
5. Conceiving a new method, based on inverse analysis and finite element method, in order to identify with a high precision of the mechanical characteristics of the composite materials manufactured by impregnating fabrics;
6. Designing and realising experimental layouts but also modifying existing testing setups that would contribute to realising experimental researches on the composite materials manufactured using impregnated fabrics or unimpregnated fabrics;
7. Realising experimental researches for identifying the mechanical characteristics of yarns that form the base of the composite materials reinforced with fabrics at different load speeds and different load temperatures;
8. Elaborating comparative studies based on experimental researches regarding the coated or uncoated fabric materials and regarding the influence of stress concentrators on these materials;
9. Realising a study based on experimental researches concerning the possibility of replacing the silicone as coating material for the manufacturing of airbags with other types of oxides.

3. THE MECHANICAL BEHAVIOUR OF THE FABRICS USED FOR THE MANUFACTURING OF THE COMPOSITE MATERIALS

Chapter three presents the types of fabrics that are used for the manufacturing of the composite materials that have as support textile materials. The fabric is a textile product obtained by crossing under a right angle two fibre systems, the warp and the weft, in a certain order. The manner in which the warp fibres cross the weft fibres is called link. Also in this chapter there is presented the classification of fabrics by several criteria: by the nature of the raw material, by destination, by the technological process of weaving or finishing and by the width of the weaving machine.

Another subchapter of the Ph.D. thesis presents the properties of fabrics used for manufacturing airbags, namely the physical, mechanical and functional properties.

A third subchapter is dedicated to the types of basic links used in the woven materials that serve as support for airbags.

Basic weaves are weaves in which, within the limits of connection ratio, each warp fibre has a single connection point with the weft fibres and each weft fibre has a single connection point with the warp fibres.

The weave is defined through two important elements: the linking ratio and the displacement. The displacement is the distance of the linking point of a fibre from the linking point of the previous fibre.

The basic links presented in the current thesis are:

- the plain weave, with a ratio of 2/2;
- the twill weave, with the smallest ratio: 3/3;
- the satin weave, with the smallest ratio: 5/5.

The fourth subchapter of this chapter presents the theories that describe the nonlinear ratios between the stress and strain in fabrics, focusing more on the woven materials than on the knitted ones.

As it is known, the mechanical behaviour of weavings and knitting’s is, usually, a nonlinear behaviour. It should be noted that the weavings and knitting’s consist of yarns and initially have a high flexibility. There are two reasons that explain this flexibility. The first is the flexibility of the yarn itself, whose structure consists of parallel, thin fibres in which the movement of the individual fibres is limited only by the friction between fibres during the loading. The other reason is that the structure of weavings and knitting’s consists of fibres connected without any type of fastening in the places where they intersect. This means that the displacement of fibres and yarns in this structure during the application of a load is complex and that their mechanical properties must be considered as a structural assembly and not as a material continuum. For a better understanding of the mechanical behaviour of the fabrics discussed in the thesis, there is presented the mathematical model of Kawabata, a model that is also implemented in the commercial software packages for simulation through the finite element method. This model is based on the biaxial extension theory of yarns.

The loading process of fabrics is divided into two stages. The first stage is the bending one, in which the fibre is stressed at pure bending, without being subjected also to tensile stress. The second stage is the one in which the bent fibre is subjected to tensile stress in the connection points between warp and weft. From the combination of the two types of loads and based on the stresses occurring in the fabric fibres there can be obtained the complete stress-strain relation for these textile materials. There are taken into account two cases, the case of the incompressible yarn and the case of the compressible yarn. At the end there is introduced into the model also the shear deformation theory. The main characteristic of the shear deformation theory is given by the torque that appears at the intersection of the woven fibres. This appears in the weaving process as a consequence of the need to change the angle between weft and warp.

The last subchapter of this chapter is dedicated to conclusions. The study of the mechanics of fabric materials has been applied to everything from airships to bullet-proof protections. Kawabata's method of the unit cell proved to be efficient in evaluating the mechanical behaviour at the uniaxial tensile test, but the prediction of the shear behaviour had less success. Continuous-type approaches are easy to implement for the structure analysis, but require a large amount of tests to present the anisotropic and nonlinear nature of the fabric. The 3D finite element models offer the most details regarding the mechanical behaviour of the fabrics, but are very demanding from the point of view of calculation needs for the modelling of large structures. The current high-end techniques offer a favourable compromise between the methods with mechanicist unit cell and finite element analysis, offering precision and detail without an extensive calibration of the elastic constants.

4. NUMERICAL SIMULATION OF THE MECHANICAL BEHAVIOUR OF THE COMPOSITE MATERIALS REINFORCED WITH FABRICS

Chapter four is dedicated to the numerical simulations using the finite element method. In the first part of this chapter there were carried out numerical analyses using the finite element method applied at mesoscopic level (at the level of fibres composing the fabric) and in the second part analyses at macroscopic level, considering the composite material as a whole.

In order to study the mechanical behaviour of the various types of fabrics, the author has preferred to use the finite element method, in a first stage, applied to a static analysis, at mesoscopic level. This method was chosen because it allowed the realising of a comparative study between the various types of fabrics with regard to the values of the nodal displacements, major and minor strains and of the stresses present at the same value of the load. For this purpose, there were modelled four types of polyamide 6.6 fabrics: plain weave, basket weave, satin weave și twill weave. The meshing of the model in finite elements was done using the "free mesh" method, but there were controlled the maximal size of the element and the manner in which the transition from large size elements to small size elements occurs.

All unfolded analyses were static type analyses, at which the applied loads and constraints are independent of the time. This type of analysis was chosen because dynamic analyses would require a much higher amount of time but also a considerable amount of memory from the computing system. The analyses that were carried out were: four analyses for uniaxial tensile tests for the four types of weaves (without defects), four analyses for biaxial tensile tests for the four types of weaves (also without defects), three analyses for uniaxial tensile tests for three types of weaves with defects (without twill weave). The introduced defects consisted in the interruption of one or several fibres located on a direction perpendicular to the loading direction.

The results that were evaluated for each type of weave of the four ones mentioned above, for the static analyses at mesoscopic level were: the Von Mises equivalent stress [MPa], the Von Mises equivalent strain [mm/mm] and nodal displacements [mm]. Figures 1 ... 4 present the results of the nodal displacements for the biaxial tensile test analysis for the four types of weaves analysed.

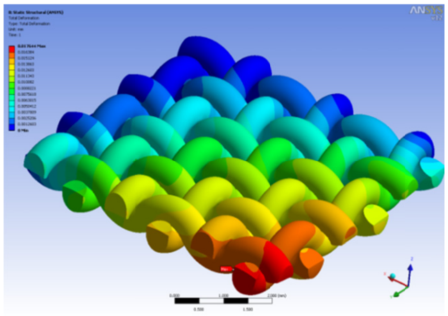

Fig. 1 The nodal displacements results for a plain weave subjected to biaxial tensile test [mm]

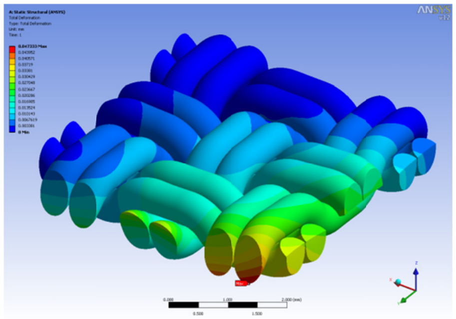

Fig. 2 The nodal displacements results for a basket weave subjected to biaxial tensile test [mm]

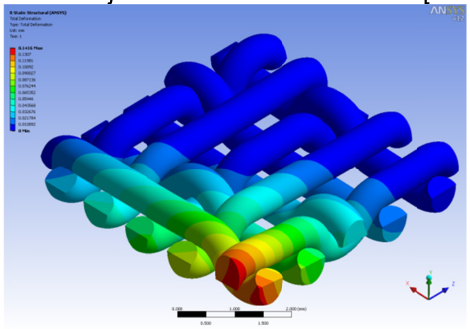

Fig. 3 The nodal displacements results for a satin weave subjected to biaxial tensile test [mm]

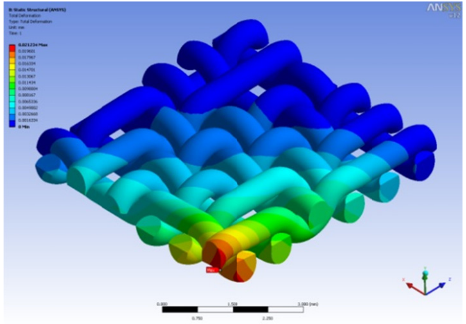

Fig. 4 The nodal displacements results for a twill weave subjected to biaxial tensile test [mm]

Following the unfolding of the static analyses for the uniaxial tensile test, there can be drawn following conclusions: the maximal value of the Von Mises equivalent stress occurs in the case of the twill weave, 61.34 MPa, being followed by the basket weave with 53.17 MPa, the satin weave with 38.08 and the plain weave 26.69, the lowest values of the nodal displacement being determined for the plain weave (0.023 mm) and the twill weave (0.024 mm).

Following the unfolding of the static analyses for the biaxial tensile test, there can be drawn following conclusions: the maximal value of the Von Mises equivalent stress occurs in the case of the satin weave – 128.9 MPa, being followed by the basket weave with 67.11 MPa, the twill weave, 61.92 MPa and the plain weave 37.35, the lowest values of the nodal displacement being determined for the plain weave (0.012 mm) and the twill weave (0.020 mm).

The analyses at macroscopic level were dynamic explicit analyses and based on them there was elaborated a method of identifying the material properties that are introduced as input data in simulation software systems based on inverse analysis.

The study of the behaviour at mesoscopic level is surely very useful when studying the behaviour of a unit cell or of a few such cells. Due to the manner in which the model is built, there are limits because of the number of finite elements. Also, there can be studied only static or quasi-static behaviours, also due to the large number of elements that are necessary. In the case that is most often encountered, that of the study of the behaviour of complex parts, it is necessary to use another approach, namely the macroscopic one. This approach implies the geometrical modelling of the whole part and its discretisation with solid-type or shell-type elements that would reflect the fabrics' behaviour at macroscopic scale.

In a first phase there were realised two explicit dynamic analyses for simulating the uniaxial tensile test and for simulating the Bias test. The Bias test is a test that aims to emphasise the shear behaviour of fabric materials or of composite materials reinforced by fabrics. Specific for this test is the fact that the rectangular shape sample, is extracted on a direction at 45^0 from the direction of the warp yarns and implicitly also from the direction of the weft yarns. Another particularity of this test is that the sample has to have the width equal to half of its free length (the length between the jaws).

The analysis phase is realised, for both simulations, using the software Ls-Dyna 971. For the test sample's material there was used the material model Composite Fabric (material no. 34 from the material library of Ls-Dyna). The finite element type was Thin Shell 163 with a number of 7 integration points along the shell thickness.

For certain nodes in the mesh there are determined boundary conditions, in the current case with regard to the fastening of the test sample in the area of the fixed jaw or for imposing movement conditions in the area of the mobile jaw. For this, there were created two nodal components (called ”fixed” and ”mobile”). In the following, there is described the temporal evolution of the analysis, by defining the value of the time increment and the needed number of increments. Figures 5 and 6 show the results obtained for the two simulations for the major strain ε_1 (for the uniaxial tensile test) and the Von Mises equivalent strain ε_{VM} (for the Bias test), respectively.

When comparing the maximal value of the major strain ε_1 at the end of the hub (34 mm) for the uniaxial tensile test with the value obtained after the experimental testing at uniaxial tensile test on weft direction of a test sample coated with silicon, there can be noticed a good agreement in terms of the result: 26.97% – at the simulation and 27.23% obtained experimentally. The same can be said about the results of the Bias test.

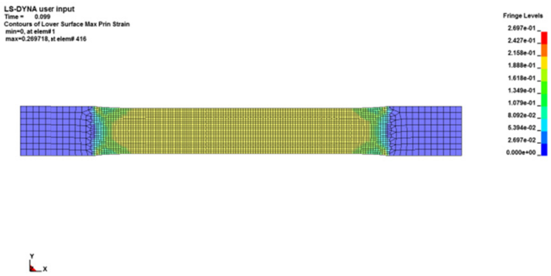

Fig. 5 The major strain ε_1 obtained for the uniaxial tensile test

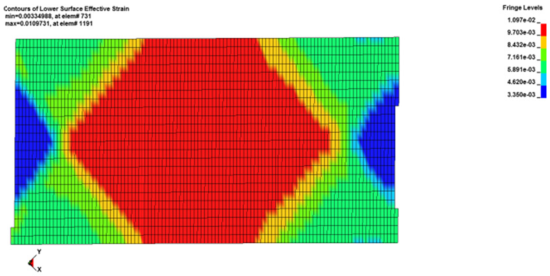

Fig. 6 The Von Misses equivalent strain ε_{VM} obtained for the Bias test

In the following there was run an inverse analysis for determining the material parameters introduced into the simulation software for the composite materials reinforced by fabrics. The originality of the method for determining the parameters that define the mechanical behaviour law through inverse analysis, consists in the fact that instead of the classical methods for determining the factors that define the materials' behaviour, methods that do not take into account the real conditions to which the blank material is subjected, the proposed method takes into account the loading state present in the material and determines the parameters with an error that is as small as possible.

The inverse analysis consists actually in the geometrical modelling, using the finite element method, of the physical model on which the researches will be carried out, and in the simulation of the real process. In parallel to this, the physical model is loaded in conditions that are identical to those applied to the discretised geometrical model, measuring certain feedback parameters. The principle of identifying the parameters (*P*) that define the behaviour laws is to determine the behaviour coefficients that reduce a function "cost" (*Q*) that expresses actually the difference between the value calculated based on the numerical simulation and the one measured during the experimental research.

During the present optimisation analysis it was sought to identify the correct values of the material data based on the equibiaxial tensile test. Thus, as optimisation method there was chosen the response surface methodology and as objective functions there was chosen two criteria, namely a criterion for force and a criterion for the major strain ε_1.

The parameters that will be optimised are, as already mentioned, the material data of the material model 34 (Fabric) from Ls-Dyna. More precisely, these parameters are: Young's modulus on warp and weft direction, transversal modulus, Poisson's ratio and the friction coefficient between the test sample made of polyamide fabric and the metallic punch. Based on the optimisation analysis, following optimal values for the material data and the friction coefficient were obtained: Young's modulus on warp direction E_A = 4020 MPa, Young's modulus on weft direction E_B = 4910 MPa, transversal modulus G_{AB} = 891 MPa, Poisson's ratio ν_{AB} = 0.356 and the friction coefficient μ = 0.11.

Figures 7 and 8 present the results obtained for the equibiaxial tensile test with the material data obtained following the optimisation analysis and the results obtained experimentally for the same test.

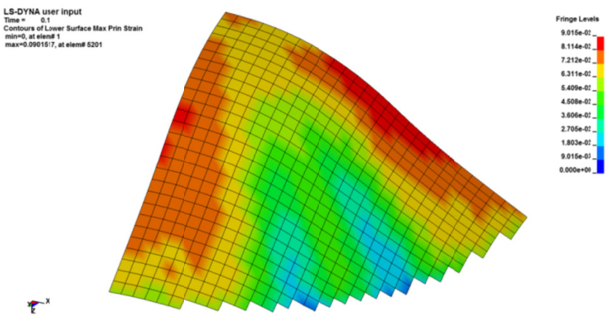

Fig. 7 The major strain ε_1 in the final stage obtained from the numerical simulation with material parameters identified from inverse analysis

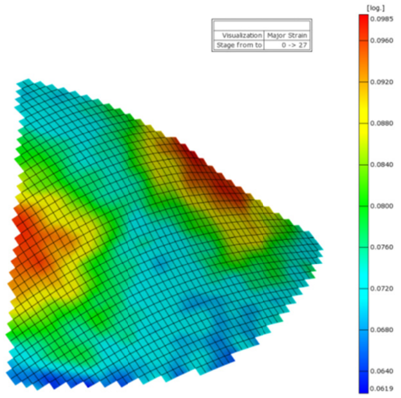

Fig. 8 The major strain ε_1 in the final stage obtained experimentally using the optical device Aramis

It can be noticed that the results are very close, not only from the point of view of the maximal values of the measured parameters, but also from the point of view of the distribution of strains on the surface of the test sample.

5. EXPERIMENTAL RESEARCH METHODOLOGY AND THE EXPERIMENTAL LAYOUTS USED

The experimental researches carried out in this thesis can be grouped on two directions, namely: experimental researches that aimed at determining the real material characteristics of polyamide PA 6.6 yarns used both for the numerical simulation (analysis through the finite element method) and experimental researches related to the mechanical behaviour of polyamide PA 6.6 fabrics coated or uncoated with silicone or with other oxides that appeared more recently in the textile industry.

The elaborated experimental research methodology aims at comparing the results obtained theoretically with those determined experimentally in order to validate the theoretical results obtained by numerical analysis, using the finite element method, with regard to the behaviour of the composite materials reinforced by fabrics.

The researches were carried out using experimental installations from the the ”Lucian Blaga” University of Sibiu, from the University of Debrecen or from specialised companies present in Sibiu:

- Universal tension, compression and buckling testing machine Instron 5587;
- Universal tension, compression and buckling testing machine Instron 4303;
- Aramis optical device;
- SEM electron microscope for determining the microstructural behaviour.

The universal tension, compression and buckling testing machines Instron 5587 and 4303 are universal testing instruments consisting of two main systems: a mobile beam and the control system, that applies the tensile or compression loads to the material. The Aramis optical device allows the determination of strains both at the uniaxial tensile test or Bias test and at the equibiaxial test. A Scanning Electron Microscope – SEM is an electron microscope that produces images of the studied test sample by scanning it with a focused electron beam. The electrons in the beam interact with the atoms in the sample and produce signals that can be detected optically and that contain information on the topography of the sample's surface, but also on its composition.

In order to realise the experiments in practice it was necessary to design several experimental installations that would allow the applying of the various work variants. Among the designed installations, one is for determining the mechanical characteristics of fabrics subjected to uniaxial stress and is used also for the Bias type test, another is used for determining the shear behaviour of this type of materials and a third one is dedicated to equibiaxial tensile tests.

The installation used for the uniaxial tensile tests and for the Bias test (Fig. 9) consists of two identical parts. The upper part is fastened on the upper beam of the Instron machine (1) that glides on the guiding columns (2). The upper part (4) is fastened to the force transducer (3) by means of a flange. The lower part of the installation (5) is fastened, also using a flange, on the table with ”T” type grooves (6) by means of six M10 screws. On its turn, the table with ”T” type grooves is fastened to the chassis of the machine (7) also by means of screws. The installation is conceived so that when the mobile beam moves, the textile sample would not unfold from the roll on which it was placed.

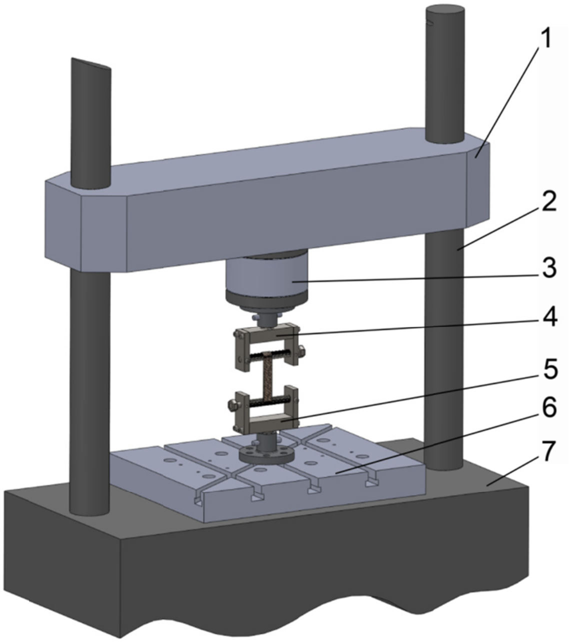

Fig. 9 The installation for realising the tensile test and the Bias test fastened on the universal tensile, compression and buckling testing machine Instron 5587

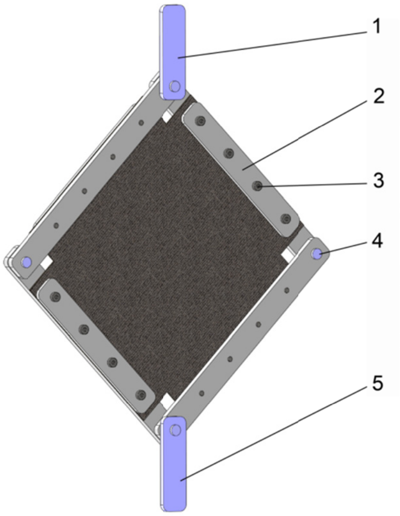

Fig. 10 Installation for determining the shearing behaviour

Another test that uses the installation from figure 10 is the frame test for composite materials reinforced by fabrics. For this test, a metal frame consisting of four arms of equal length (2) is fastened on a uniaxial tensile testing machine by fastening the upper free end (1) into the upper jaw (the mobile jaw) while the lower end (5) is fastened in the lower jaw (the fixed jaw). The test sample made of the textile composite material is fastened between the arm pairs (2) on which, in order to avoid crushing the material, there were glued rubber bands that also help to increase the adherence between the test sample and the fastening system. Each side of the test sample is fastened by means of four M5 screws (3). In order to avoid a folding of the material, the test sample has cut outs in the four corners. On the other diagonal of the test sample there are also two cylindrical joints (4) that allow the arms to rotate.

6. EXPERIMENTAL RESEARCHES REGARDING THE BEHAVIOUR OF THE COMPOSITE MATERIALS REINFORCED BY FABRICS

The experimental researches presented in this Ph.D. thesis are structured on two important directions, namely the behaviour of the materials composing the composite materials with textile support and the behaviour of the composite materials reinforced by fabrics.

In order to carry out the experimental researches regarding the mechanical characteristics of the polyamide PA 6.6 fibres, there has been set up an experimental research algorithm that contains following stages: emphasising and hierarchisation of the significant factors, selecting the mathematical models of the considered characteristics, programming the experiment, selecting the experimenting conditions, carrying out the experiments, determining the models' coefficients, checking the adequancy of the determined models, checking the coefficients' significance and determining the confidence intervals.

In this case, there has been used a factorial experimental programme of type 3^2 in which the independent variables (loading speed and loading temperature) were modified on three variation levels. This programme contains nine experiments, but in order to determine the experimental error in each experimental point, the whole programme was repeated five times, thus leading to a number of 45 experiments.

From the graphs obtained for the tensile tests for polyamide PA 6.6 it can be noticed that there exist two distinct areas on the true stress-true strain curves. The first area is the starting area which defines the hyperelastic behaviour of polyamide PA 6.6. The second area is characterised by the sudden drop of the stress value, indicating the decrease of the tensile capability of the fibre. The last area also contains the area where the material breaks.

The graphs in figures 11 and 12, respectively, present the dependence of the true stress and true strain of the two analysed parameters.

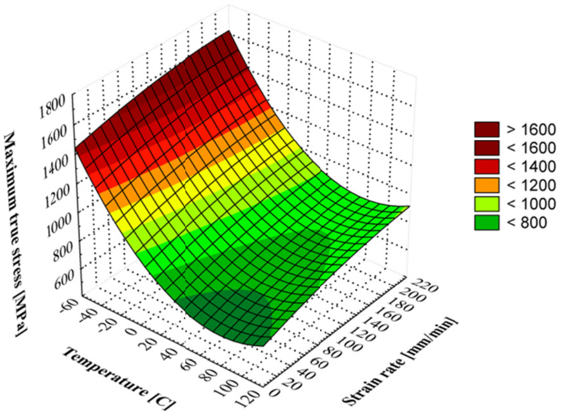

Fig. 11 Dependence graph for the maximal true stress function of *T* and *v*

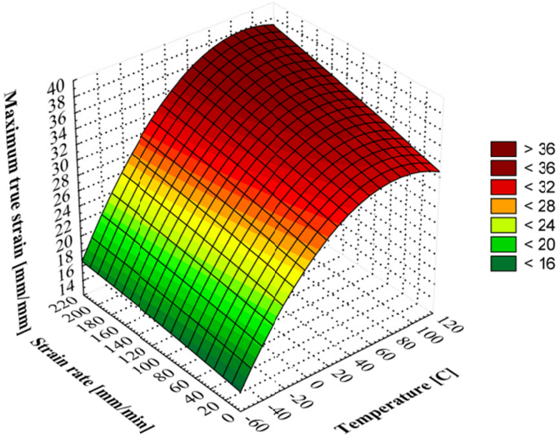

Fig. 12 Dependence graph for the maximal true strain function of *T* and *v*

The main conclusion that can be drawn is that the ultimate strength of the polyamide PA 6.6 decreases with the increase of the temperature and increases with the loading speed.

In order to determine the behaviour of the composite materials reinforced by fabrics from a macrostructural point of view (given the need to input the material data into the numerical simulation software), there were employed some types of mechanical tests such as the uniaxial tensile test, the equibiaxial tensile test, the Bias test and the shear test or frame test.

The oldest method for testing the materials' behaviour is the uniaxial tensile test. The test sample is fastened at both ends and loaded at a speed that can be constant or not, on a tensile testing machine, until failure occurs. The applied force is measured using a force transducer, while the elongation (strain) is measured using an extensometer. For the unfolding of the researches, there was used the experimental installation designed for avoiding the crushing of the fibres, the universal tensile, compression and buckling testing machine Instron 5587 and the optical device Aramis (fig. 13). The obtained data can be represented graphically directly in coordinate's force-elongation (fig. 14).

For unfolding the tests there were extracted sets of five test samples for each material type, i.e. for basic (uncoated) polyamide PA 6.6 fabric and for polyamide PA 6.6 fabric coated with silicone both on the direction of the warp fibres and on the direction of the weft fibres. The shape of the test samples was the standard one for this type of test.

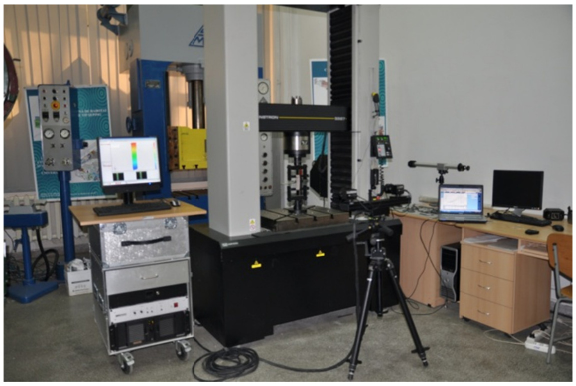

Fig. 13 The testing machine Instron 5587 with the optical measurement system Aramis used for the uniaxial tensile tests

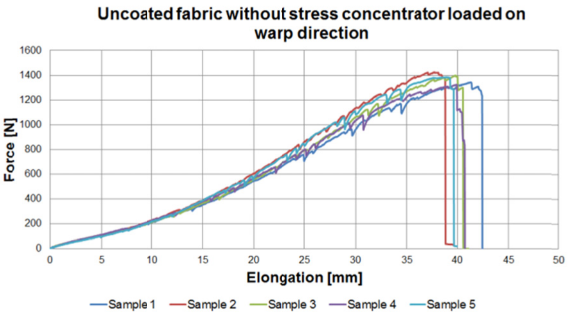

Fig. 14 The characteristic force-elongation curve for test samples that were not coated with silicone, without stress concentrator and loaded on the direction of the warp fibres

The main conclusions that can be drawn after the experimental uniaxial tensile tests for coated or uncoated fabrics, extracted on the direction of the warp or weft fibres, are as follows:

- at the uniaxial tensile loading, the maximal force has higher values if the loading is done on the warp direction than if the loading is done on the weft direction;
- at the uniaxial tensile loading, the maximal elongation has higher values if the loading is done on the weft direction than if the loading is done on the warp direction;

Because these composite materials reinforced by fabrics are materials that are used for the manufacturing of airbags, they will not be found in the airbags in the same shape as delivered from weaving machines, but will undergo a series of perforations of different diameters needed for the assemblage, for the introduction of the pyrotechnical cap etc. Therefore, it has been considered as useful to carry out a comparative study between the behaviour of these materials, coated with silicone or uncoated, in the case when there exists a stress concentrator and when such a stress concentrator does not exist, respectively. The shape of the test samples was the standard one for this type of test, but, supplementary, each test sample was perforated in its centre with a hole of diameter Φ 10 mm. Figure 15 presents the failure mode of a test sample with stress concentrator, loaded on the direction of the weft fibres, while figure 16 presents the values of the major strain for the same test sample.

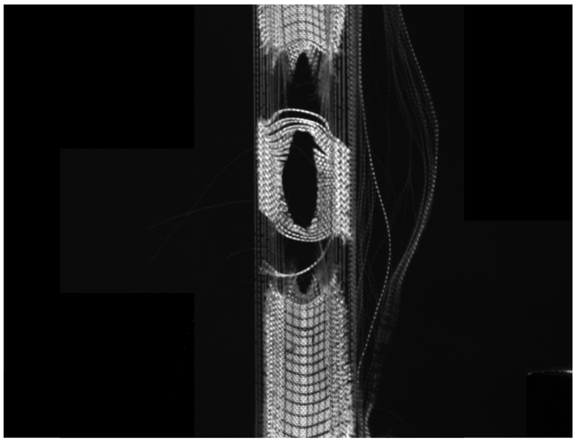

Fig. 15 Failure mode for a test sample woven of polyamide PA 6.6 coated with silicone with stress concentrator and loaded on the direction of the weft fibres

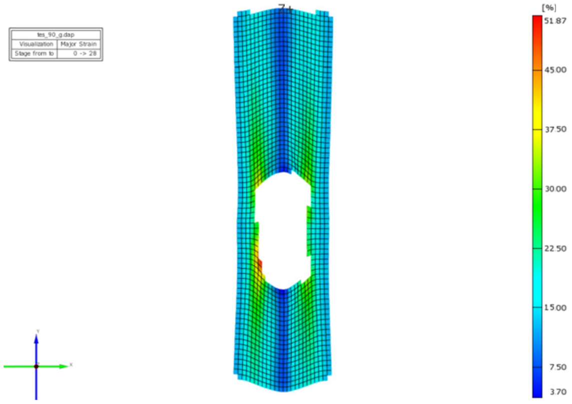

Fig. 16 Values of the major strain ε_1 for a test sample woven of polyamide PA 6.6, uncoated with silicone, with stress concentrator and loaded on the direction of the weft fibres

The conclusions that can be drawn from these tests are as follows:

- at the uniaxial tensile loading, for test samples with stress concentrator, both the value of the maximal force and the value of the corresponding elongation decrease in comparison with the case of the test samples without stress concentrator;

- at the uniaxial tensile loading, for test samples with stress concentrator, the optically determined shearing angles present values specific for the shearing stress, both for the coated samples and for the uncoated ones, but also for the samples loaded on the warp direction or on the weft direction;

However, during their functioning, airbags are not subjected to uniaxial stretching but more to biaxial stretching. Therefore, a specific subchapter aimed at emphasising the behaviour of the composite materials reinforced by fabrics to equibiaxial loading. For this test, there was used a testing installation from the endowment of the ”Lucian Blaga” University of Sibiu, along with the Aramis optical device.

For the equibiaxial tensile testing, the test samples fastened in a fastening system are loaded by means of a punch with hemispherical head. Both the force needed for the material's fastening and the active force needed for actuating the punch are realised by two distinct hydraulic circuits. Of course, from the point of view of the researches described in this thesis, the area of interest was the determining of the force-displacement curve for the punch. Using pressure sensors, a data acquisition system and the Matlab software package (also presented in chapter 5), the pressure is transformed into electrical voltage and then into force. Using a constant speed and acquiring on another channel the variable time, it was possible to determine the point pairs force – displacement for four types of test samples: coated with silicone and uncoated, with stress concentrator and without stress concentrator. The obtained data can be represented graphically directly in coordinates force-displacement.

By coupling the testing installation with the optical measurement system, there could be determined also the principal strains, the secondary strains, the equivalent strains and the size of the cap formed prior to failure.

In order to be able to determine the strains using the Aramis optical measurement system (fig. 17), the test samples were prepared through the deposition, on their surface, of fine droplets of black paint applied on a white matte plaint layer applied previously.

Fig. 17 The experimental installation with the Aramis optical measurement system used for the equibiaxial tensile tests

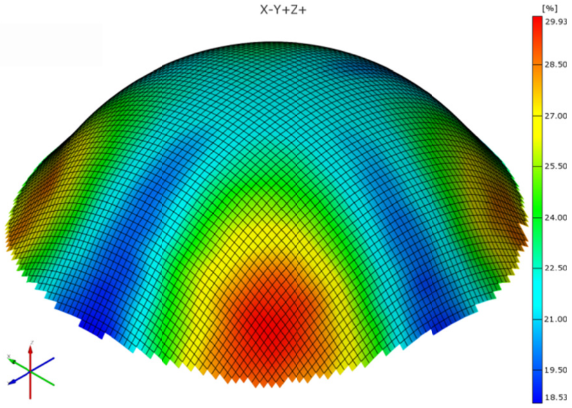

Fig. 18 The values of the principal strain ε_1 for a woven test sample made of polyamide PA 6.6 coated with silicone, without stress concentrator, subjected to equibiaxial stretching

There were carried out tests on test samples with stress concentrators and on test samples without stress concentrator, coated with silicone or uncoated. Figure 18 shows the variation of the principal strain for a test sample coated with silicone, without stress concentrator. The main conclusions that can be drawn following the equibiaxial tensile test are:

- at the equibiaxial tensile loading, both the force needed for breaking the test sample and the maximal height of the cap are larger in the case of the fabric coated with silicone;

- at the equibiaxial tensile loading, the maximal values of the principal strain occur on the direction of the weft fibres, but values that are close to these are obtained also on the direction of the warp fibres;

- at the equibiaxial tensile loading, the presence of the stress concentrator leads to a decrease of the strength by 45% and of the elongation by 24%.

Another consecrated test applied to the composite materials that contain fabrics is the Bias test. The name of this test comes from the manner of extracting the samples, namely at an angle of 45^0 from the direction of the warp fibres and of course at the same angle from the direction of the weft fibres. Actually, the Bias test is a tensile test too, but which can emphasise, due to the manner in which the test sample was extracted, the shear behaviour of the composite material or of the fabric. The test is simpler than other tests specific for shearing because it does not require using special testing installations, but only of classical testing machines. Specific for this test type is the fact that the local strains on the surface of the test sample are not at all homogeneous and there are different areas on the sample's surface, as shown in figure 19. Figure 20 presents the values of the Von Mises equivalent strain for a test sample coated with silicone and subjected to the Bias test.

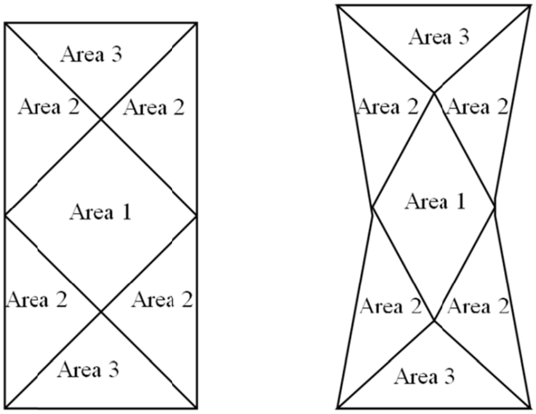

Fig. 19 The strain areas that appear on the composite test samples with textile support at the Bias test

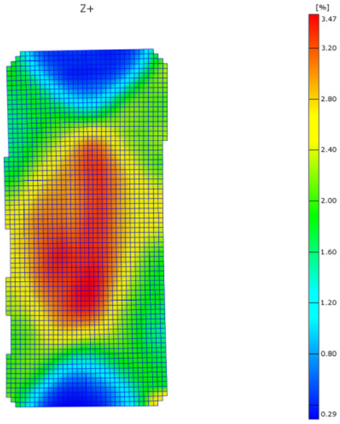

Fig. 20 Values of the Von Misses equivalent strain ε_{VM} for a test sample made of polyamide PA 6.6 coated with silicone and without stress concentrator, subjected to the Bias test

The main conclusions that can be drawn after the Bias test are as follows:

- the higher values of the maximal force that occurs during the test are for the case of the fabrics coated with silicone, as compared to uncoated fabrics;
- the elongation corresponding to the maximal force has higher values in the case of the fabrics coated with silicone that in the case of uncoated fabrics.

The test that is the most used for emphasising the shearing behaviour of the composite materials is the frame test. This test implied the realising of an experimental installation. This installation is built so that by translating its mobile end (fastened to the mobile beam of the testing machine) by means of the two joints, the test sample that is fastened by means of screws between the frame's arms is subjected to shear. The acquisition device of the Instron testing machine allows determining a curve formed of point pair's displacement-applied force. By means of simple calculations, based on trigonometric or mechanical laws, this curve can be transformed into a curve in coordinates shearing angle – shearing load (fig. 21).

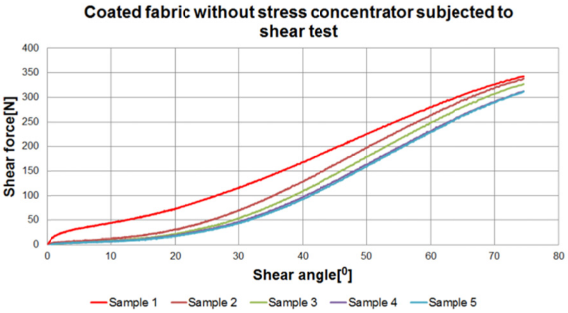

Fig. 21 The characteristic curve shearing force - shearing angle for test samples coated with silicone, without stress concentrator, subjected to the shearing test

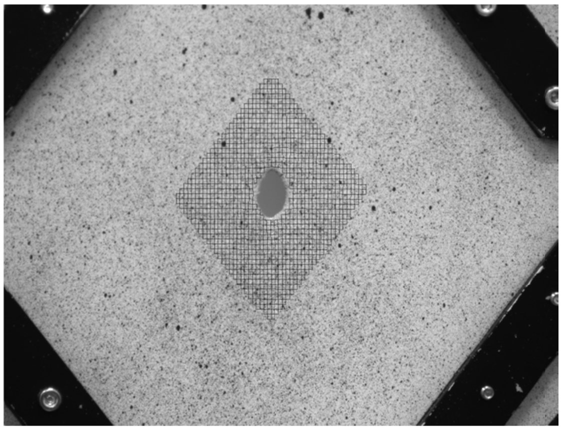

Fig. 22 Area measured using the optical measurement system, in the final stage

As in the case of the other experiments, there were realised tests for samples with stress concentrator and without stress concentrator. At the shearing test, it can be noticed that the presence of the stress concentrator is not as important, the maximal value of the shearing force with stress concentrator being very close to that of the sample without stress concentrator. The differences between the samples coated with silicone and the uncoated ones are also rather small, the maximal value being obtained for the coated ones.

It can be noticed that lately, at world level, there were several attempts to replace silicone at the manufacturing of airbags. This is due to the fact that silicone ages and, when subjected for longer periods to extreme temperatures (high temperatures or low temperatures) it loses some of the mechanical properties for which it is used. The newest researches in this domain are represented by the usage of nanocomposites at the manufacturing not only of fabrics for airbags but also of products for a wide range of other branches of the automotive industry or of the consumer goods industry.

The first researches concerning the usage of nanotechnologies applied to textile fibres are of very recent date, namely from 2009. In this thesis the author has limited herself to obtaining four nanocomposite materials based on the polyamide PA 6.6 fabric used also in the other researches, on which there were deposited nanoparticles of WO_3, SnO_2, MnO and ZnO, due to the high costs involved and the difficulties in realising these materials. In order to achieve a good reproductibility of the results, there were realised 5 test samples for uniaxial tensile testing only on the direction of the warp fibres (also out of economic considerate) and 5 test samples for the equibiaxial tensile testing.

Figures 23 and 24 present images realised for the uncoated polyamide fabric (fig. 23) and the nanocomposite material realised from polyamide PA 6.6 fabric and ZnO nanoparticles (fig. 24) at magnifications of 1000 X and of 1500 X, respectively.

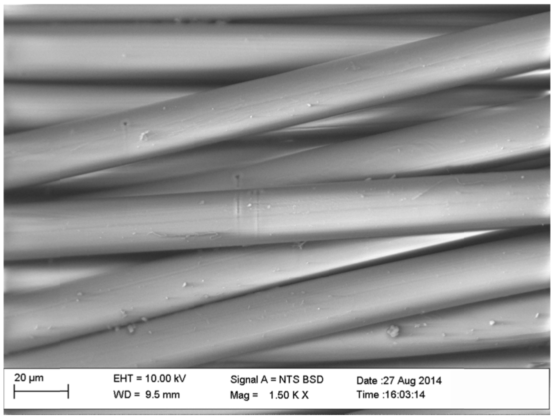

Fig. 23 Image from the SEM microscope of the uncoated polyamide PA 6.6 fabric, at a magnification of 1500 X

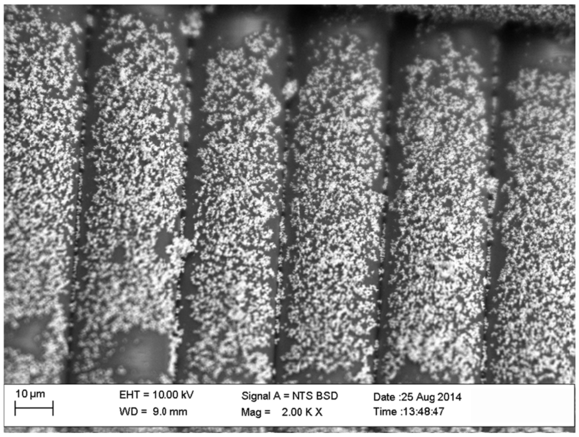

Fig. 24 Image from the SEM microscope of the nanocomposite material consisting of polyamide PA 6.6 fabric and ZnO nanoparticles, at a magnification of 2000 X

The conclusions that can be drawn from these tests are:

- both from the point of view of the uniaxial behaviour and from the point of view of the equibiaxial behaviour, the composites with ZnO and MnO nanoparticles behave the best, while the behaviour of the fabrics coated with SnO_2 and WO_3 have a behaviour close to that of the uncoated fabric;

- it can be said that the nanocomposite material with ZnO nanoparticles could replace the silicone in a not very far future, if the manufacturing costs could be reduced.

7. FINAL CONCLUSIONS. THE MAIN ORIGINAL CONTRIBUTIONS OF THE THESIS

Through the current thesis there have been brought a series of original contributions with regard to the mechanical behaviour of the composite materials with textile support coated with silicone or other types of oxides, contributions published by the author in Romania and abroad or to be published soon, as follows:

From a theoretical point of view:

- there have been synthesised as a bibliographical study, most of the scientific and technical results published with regard to the composite materials reinforced by fabrics;
- there has been elaborated an original classification of the textile materials that compose the composite materials;
- there have been identified the forming mechanisms of the composite materials reinforced by fabrics (weavings or knitting's);
- the state of the art with regard to methods and techniques used in the numerical simulation of composite materials reinforced by weavings or knitting's has been determined;
- there has been synthesised the state of the art of the experimental researches for these types of materials, identifying the types of loads and implicitly the mechanical tests to which these materials can be subjected;
- a study has been elaborated regarding the modelling of the mechanical haviour of the composite materials reinforced by fabrics, emphasising the representative mechanical models of unit cells;
- there have been realised three dimensional geometrical models for four types of fabric (plain, satin, basket and twill weaving) in order to export these models into a software for analysis through the finite element method;
- there have been realised numerical simulations through the finite element method in linear domain, at mesoscopic level, for four types of weavings, targeting the determination of the von Mises equivalent stress, of the equivalent strain and of the nodal displacements for the four types of weavings. Based on these numerical simulations there have been realised a comparative study regarding the behaviour of the various types of weavings at the uniaxial and biaxial tensile tests;
- an explicit dynamic analysis through the finite element method in the nonlinear domain has been realised, at macroscopic level, in order to identify the mechanical behaviour at the uniaxial tensile test of the composite materials that comprise fabrics;

- an explicit dynamic analysis through the finite element method in the nonlinear domain has been realised, at macroscopic level, in order to identify the mechanical behaviour at the Bias test of the composite materials that comprise fabrics;
- there has been realised a model of an explicit dynamic simulation, parameterised from the point of view of the material data, for the equibiaxial tensile test;
- an explicit dynamic analysis through the finite element method in the nonlinear domain has been realised, at macroscopic level, in order to identify the mechanical behaviour at the equibiaxial tensile test of the composite materials that comprise fabrics;
- an inverse analysis has been elaborated, based on the simulation in the dynamic domain of the equibiaxial tensile test, by means of which it was possible to identify with a high degree of accuracy, the material data that contribute to defining the mechanical behaviour of the composite materials that comprise fabrics;

From the experimental point of view:

The experimental researches were channelled on two directions: one for determining the real material characteristics for the polyamide PA 6.6 fibres used for the numerical simulation (analysis through the finite element method) and one for determining the mechanical behaviour of the polyamide PA 6.6 fabrics uncoated or coated with silicone or other oxides that have been introduced more recently in the textile industry.

The experimental researches related to determining the the real material characteristics for the polyamide PA 6.6 fibres comprised following original contributions:

- in a first phase, based on well determined experimental plans, there have been carried out tensile tests for three different testing temperatures and with three different testing speeds;
- an experimental programme has been designed for realising the tensile tests on the polyamide 6.6 fibres;
- the author has elaborated, in the Visual C++ software, a software product that would allow the determining of all data types needed for the tests that can be carried out on the testing machine;
- there has been carried out a statistical processing of the experimental data by applying the Student, Cochran and Fisher-Snedecor tests.

The experimental researches related to determining the mechanical behaviour of the polyamide PA 6.6 fabrics uncoated or coated with silicone or other oxides, with or without stress concentrators comprised following activities:

- there have been elaborated experimenting strategies for each of the experimental research directions taken into account;

- there have been realised two experimental installations, one for realising the uniaxial tensile tests and the Bias test and one for determining the shearing behaviour, both installations being conceived so that they can be fastened on the tensile testing machine from the endowment of the Faculty of Engineering;
- there has been adapted an installation from the endowment of the Faculty of Engineering, used for determining the forming limit curves, so that there can be realised on it equibiaxial tensile tests for the composite materials that have as support fabrics made of polyamide 6.6;
- the pressure transducer was calibrated to be used to determine the force at the equibiaxial tensile test;
- there have been realised two virtual instruments in the Matlab software, one for the signal acquisition and one for filtering the signal for determining the force at the equibiaxial tensile test;
- there have been realised experimental researches for determining the behaviour of materials woven with polyamide 6.6 coated or uncoated with silicone, with or without stress concentrators, at the uniaxial tensile test for test samples extracted on the direction of the warp fibres and on the direction of the weft fibres;
- there have been carried out experimental researches for determining the behaviour of the materials woven with polyamide 6.6 coated or uncoated with silicone, with or without stress concentrators at the Bias test;
- there have been carried out experimental researches for determining the behaviour of the materials woven with polyamide 6.6 coated or uncoated with silicone, with or without stress concentrators at the shearing test;
- there have been carried out experimental researches for determining the behaviour of the materials woven with polyamide 6.6 coated or uncoated with silicone, with or without stress concentrators at the equibiaxial tensile test;
- there have been realised analyses using a SEM microscope for fabrics made of polyamide 6.6 impregnated with various oxides;
- there have been carried out experimental researches for determining the behaviour of the materials woven with polyamide 6.6 coated with other oxides, without stress concentrators at the uniaxial tensile test;
- - there have been carried out experimental researches for determining the behaviour of the materials woven with polyamide 6.6 coated with other oxides, without stress concentrators at the equibiaxial tensile test;

Future research directions

The topic tackled in the current Ph.D. thesis contributes to a better knowledge of the mechanical behaviour of the composite materials that comprise in their structure fabrics. Taking into account the current trends at world level in the area of composite materials, there can be predicted new preoccupations related to these materials, there still remaining open for tackling research directions such as:

- replacing polyamide as base material for the fabrics with other polymeric materials;
- modifying the fabric type (plain weaving) with other fabric types;
- studying the influence of other oxides used as coating materials not only on the mechanical behaviour, but also on the thermal behaviour of these materials, especially since the usage of silicone appears to become uncertain due to the fact that the coating procedures are not ecological;
- elaborating mathematical models that are closer to the real behaviour of these materials than the ones currently in existence;
- realising specific material subroutines for each type of weaving and of coating, that would take into account all stresses to which these materials are subjected;
- realising rheological studies that would emphasise the friction behaviour of these materials.