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Biaxial Testing of Fabrics - A Comparison of Various Testing Methodologies

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***Abstract*—**In textile industry, besides the conventional textile products, technical textile goods, that have been brought external functional properties into, are being developed for technical textile industry. Especially these products produced with weaving technology are widely preferred in areas such as sports, geology, medical, automotive, construction and marine sectors. These textile products are exposed to various stresses and large deformations under typical conditions of use. At this point, sufficient and reliable data could not be obtained with uniaxial tensile tests for determination of the mechanical properties of such products due to mainly biaxial stress state. Therefore, the most preferred method is a biaxial tensile test method and analysis. These tests and analysis is applied to fabrics with different functional features in order to establish the textile material with several characteristics and mechanical properties of the product. Planar biaxial tensile test, cylindrical inflation and bulge tests are generally required to apply for textile products that are used in automotive, sailing and sports areas and construction industry to minimize accidents as long as their service life. Airbags, seat belts and car tires in the automotive sector are also subject to the same biaxial stress states, and can be characterized by same types of experiments. In this study, in accordance with the research literature related to the various biaxial test methods are compared. Results with discussions are elaborated mainly focusing on the design of a biaxial test apparatus to obtain applicable experimental data for developing a finite element model. Sample experimental results on a prototype system are expressed.

***Keywords*—**Biaxial Stress, Bulge Test, Cylindrical Inflation, Fabric Testing, Planar Tension.

I. Introduction

IN textile industry, besides the conventional textile products, technical textile goods which have superior functional properties are being continuously developed for daily use. Such products include textiles materials having primarily functional properties and high level of technical performances other than conventional textiles. Popular fibers used in the production of technical textiles are natural and manmade fibers such as cotton, glass, aramide, polypropylene, polyamide, polyester and similar [1]. These products are mainly produced with weaving technology and are widely preferred in areas such as sports, geology, medical, automotive, construction and marine sectors.

Airbags in automobiles is one of the main security equipments that are obliged to exist in cars as a major hardware of passive security. Biaxial tests are mandatory for providing data during their design process and thus their proper functioning, which in terms serve to saving lives in unavoidable accidents.

Such textile products subject to engineering use are subject to multi-axial stress states and exhibit large deformations and strains under typical conditions of use. At this point, sufficient and reliable data cannot be obtained with conventional uniaxial tensile testing for determination of the mechanical behavior of technical products. This is mainly due to their being exposed to complex biaxial stress states, which cannot be extrapolated from uniaxial conditions due to high nonlinearity involved. Therefore, to overcome these drawbacks in numerical analysis prior to application, the most preferred multi-axial testing method is biaxial tensile testing. These tests and analyses are applied to fabrics with different functional features in order to determine several characteristics and mechanical properties of the product for use in numerical analysis.

In the literature, the main tests of similar type are the planar biaxial tensile test, cylindrical inflation tests and bulge tests that are applied for such textile products. These data help to minimize unforeseen mechanical failure through their service life. Additionally material properties of textile-like sub-components of airbags, seat belts and especially ply-supported car tires in the automotive sector are subject to same biaxial stress states are also characterized by the same type of experiments.

In this study, research literature related to the various biaxial test methods are overviewed, and numerical data from some of them are compared. Results with discussions have been aimed at designing a biaxial test apparatus to obtain and compare experimental data to develop comparable and useful data for use in a finite element model.

II. The Airbag

Passenger safety is of prime importance in modern transportation vehicles. For this purpose, airbags and safety belts have used to protect the passenger in crashes as part of modern safety systems [2,3]. Thus, automotive industry is one of the main markets for technical textiles [4]. Following extensive R&D, they were started to be used in the vehicles as airbags after safety belts at the end of 1980’s against crashes [5]. At the moment, a vehicle has about 9 airbags as a standard application [6]. The market of airbags is 4 billion dollars and every year a steady increase is expected [7].

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An airbag is composed of 3 parts namely airbag fabric, gas generator and sensor. The sensor is composed of electronic components and the sensor, control unit and cable-net work synchronically [8]. Gas generator is triggered by a series of parameters like impact, acceleration, speed change and the airbag starts to inflate [6] as a result of impact (crash). Inflation time is about 25-30 milliseconds [8]. In other words, the opening speed of airbag reaches 160 km/h [9]. The pressure and temperature of gas in the airbag also reaches to 70kPa and 600° C respectively. As a result of the designed distribution of gas pressure, the airbag damps the kinetic energy of the passenger [10].

The behavior of airbag used in the vehicle changes according to their place and position. As a result of this, some technical differences can be seen between the airbags used for the driver and the passenger [6]. In order to meet the required fabric properties, the airbag fabric is woven from polyamide (nylon) 6.6 yarns. [11]. Plane weave is used to have maximum contact between the warp and weft yarns of the fabric. The fabric behaves mechanically anisotropic and nonlinear form. The nonlinear behavior is obtained as a result of inner changes along the deformation. Polyamide has a high melting point and its moisture regain is around 4 %, which support extinguishing by water emersion. Accordingly, the hot particles, which may escape from the inflator to the inside of airbag, cannot burn the airbag [12]. The fabric can be additionally protected by elastomers wrapping. [13].

New fabrics contact the skin of passenger more softly and have a better folding property during the clash [12]. Today, the high strength and finer yarns (from 235dtex to 350dtex) are used in fabric production. In the future, the airbags will be lighter, more resistant and in denser structure due to the use of finer, higher strength yarns [7]. Depending on the fabric developments the methods of analysis and design will have to be developed as well.

During the inflation and deflation cycle, the airbag is subjected to high thermal and dynamic stresses as the gas exhausted is at a very high temperature and carries particles. Thus, the airbag material should also be flame and heat resistant and its melting point should be very high. For the airbag fabrics, the strength and elasticity should be very high but the initial modulus, in order to prevent any bursting. The possible regional tensile stresses are spread out along the fabric surface and any tear due to the high stress is prevented.

The design of airbags has to be made by the extensive numerical methods as the experimental equipments used are too expensive today. Fabric properties of airbag are of primary importance for the protection of people when they are in contact with airbags [14]. Basically, these fabric properties affect the performance properties of airbag required. Yarn type, yarn density, strength and extension of yarn and fabric, weave, and weight of fabric, air permeability, tear strength and bursting strength are the main parameters involving the behavior of airbags [15].

III. Tests in Characterizing Planar Materials for Engineering Analysis

In order to have consistent and realistic analysis, mechanical properties of textiles incurred have to be modeled based on its complicated structure. The purpose tailored models can only be realized by only the reflection of mechanical properties of woven fabric directions into continuum as stated by Marklund and Nilsson [16]. Technical textiles used in airbags are subjected to multi axial stresses and large deformations. Uniaxial tensile analysis does not provide sufficient data to determine the mechanical properties of the technical product, which is subjected to biaxial and sometimes local tri-axial apparent stress states. Effective modeling techniques can be used for optimizing the fabric design with numerical methods so that technical textiles can be further developed for the end use. New technologies necessitate the models representing the fiber and the fabric behaviors comprehensively. Numerical modeling methods are good tools to estimate the fabric properties without testing actual full scale prototypes.

Many methods have been developed to determine the biaxial stresses on the warp and weft directions of fabrics (an example is in [17]) apart from ISO and EN standards which are generally based on determining simple non-engineering properties. These methods can be classified as follows:

A. Tubular Inflation Test

This test is based on clamping the specimens in tubular shape at the rigid and circular jaws. In this test, hydrostatic pressure in the tube can create a peripheral stress if the fabrics are not water and/or air permeable. In addition, axial tensile stress can independently be changed the load application on the cylinder ends and shear stress can be applied on the fabric torque application on the cylinder ends [18]. As the hydrostatic pressure changes along the fabric so the fabric behaves differently depending on its air permeability causing the problem. The fabric used for clothing cannot be tested by the cylindrical shape because of their weaknesses [19].

B. Planar Biaxial Tension Test

This method applies to the cross shaped fabric by the tensile force applications on both warp and weft directions. Load and strain are continuously recorded during the test [20] and the strain/stress curves are developed. Galliot and Luchsinger examined the relationship between the elastic properties and loading under biaxial forces. Cross-shaped specimens of PVC coated polyester fabric were tested on planar biaxial testing system and the data of stress-strain were obtained [21] up to a limit.

C. Bulge Test

The material is inflated until bursting by the pressure of water or air changing its shape to sphere. The test shows the relationship between stress and strain, as well as providing bursting strength [19]. Galliot and Luchsinger [21] calculated the oil pressure and oil flow analytically in order to determine the biaxial stress and strain at the apex of specimens.

Today, strain on the surface as well as apex of specimens can also be determined by the use of optical methods. Wei Koh [22] also worked to record the instant pressure and radius of curvature using optical methods.

D.Dynamic Bulge Testing by Split-Hopkinson Pressure Bar (SHPB) Apparatus

The SHPB experimental assembly is used to determine mechanical behavior of materials under high deformation speeds and generally compression. High strain rates from $10^2 s^{-1}$ to $10^4 s^{-1}$ can be reached but it is not possible to increase the speed further due to the limitations on instrumentation, materials used and the length/diameter ratio of the specimens, which should be within certain range [23]. Modified versions of this apparatus which enable bulge testing at small scales are available. However, for available dimensions, continuum results cannot be easily evaluated.

E. Full-Scale Impact Tests

The most widely used important test is the impact test beside the other structural tests to determine dynamic air permeability, the characterization of the airbag under excessive pressure, folding effectiveness of airbag fabrics and performance of inflatable airbags. Impact tests are frequently used to evaluate the safety adequateness of the whole safety system for the driver and passengers. Impact test can carried out experimentally or by the numerical simulations. Experimental methods are carried on crashing real cars or sled systems. As the results obtained with the real cars are of course, representing a real accident, the test is highly complicated and expensive. Test dummies are developed to represent real passengers which are repetitively used in the tests [24].

IV. Materials and Methods

Fourtypes of specimens woven form Nylon 6.6 fibers (namely grey, polyurethane coated, laminated and taken from the airbag), were tested. The samples were representative of high strength technical textiles, and exhibited similar properties compared to an airbag fabric; Polyamide 6.6 is most widely preferred fiber in the manufacture of airbag as it has the highest strength/weight ratio when compared to other natural and man-made fibers and is very economical. Thus, in this work polyamide 6.6 was chosen to obtain the results to be applied in practice conveniently.

Number of thread, yarn count, weight and air permeability of fabrics used under standard atmospheric conditions (20±2 °C temperature and 65±2% relative humidity) have been tested in order characterize the fabrics. The number of threads was tested according to standard testing method EN 1049-2 [25]. The weave of fabrics were plain.The yarns taken out of the fabric were tested according to standard testing method TS 255 [26].The weights of fabric were tested according to standard testing method TS 251 [27]. For air permeability testing, a testing instrument specifically designed in ITU Textile Laboratory was used.

All the strain and displacement measurements were made by using optical measuring techniques instead of using strain gauges and mechanical extensometers since strain gauges and mechanical extensometers are sources of error for large deformation analysis [28]. Digital image correlation (DIC) method is contactless and determines the deformation and/or movement by the data is obtained via images analysis.

Uniaxial and planar biaxial test methods were conducted to analyze the stress and strain of the airbags and related textile materials since primarily, the uniaxial and biaxial tensile test apparatus were used test the behavior of fabrics. For uniaxial tensile strength testing, MTS 858 Mini Bionix II and for biaxial tensile testing, a testing instrument specifically designed in ITU Strength and Biomechanics Laboratory are respectively used. The results obtained in these simple conventional tests showed the drawbacks and difficulties of these methods. Considering all these points, a pneumatic bulge test assembly has been developed. The results obtained on two testing systems were compared to the results obtained with the bulge testing results

A. Uniaxial Tests

Uniaxial tensile strength test is carried out according to ASTM D5035 – 11 standard testing method. Three specimens (in 25 mm in width and 170 mm in length) were cut for each type of fabric for testing as seen in Figure 1. The types of specimens developed were

- Group 1 : Untreated PA 6.6 Fabric specimens in weft direction
- Group 2 : Laminated PA 6.6 Fabric specimens in warp direction
- Group 3 : Polyurethane coated PA 6.6 Fabric specimens in weft direction
- Group 4 : Untreated PA 6.6 Fabric specimens in warp direction
- Group 5 : Polyurethane coated PA 6.6 Fabric specimens in warp direction
- Group 6 : Polyurethane laminated PA 6.6 Fabric specimens in weft direction

Fig. 1 Example Specimens prepared for uniaxial tensile testing

B. Planar Biaxial Tension Tests

Testing instrument specifically designed in ITU Strength and Biomechanics Laboratory is utilized. The fabric specimens are grouped for planar biaxial testing as follows:

- Group 1 : Untreated PA 6.6 Fabric specimens
- Group 2: Polyurethane membrane laminated PA 6.6 Fabric specimens
- Group 3 : Polyurethane coated PA 6.6 Fabric specimens
- Group 4 : Untreated PA 6.6 Fabric specimens in warp direction
- Group 4 : Silicone coated PA 6.6 Fabric specimens taken from airbag fabric

Sample 1 and 4 are untreated uncoated PA 6.6 fabrics and they deformed in the required area when broken specimens were observed. The breaking stress of warp yarns is about 140MPa. Sample 2 and 6 are with polyurethane membrane PA 6.6 fabrics. No change was obtained in the tensile strengths of fabrics after the membrane was removed. So, the membrane has made no contribution to the strength of fabric. The breaking stress of this sample group is about 150MPa.

Sample 3 and 5 are polyurethane coated PA 6.6 fabrics. This coating caused to a stiff and compact handle of fabrics. This is why the fabrics have a brittle structure when stress applied. The breaking stress of this specimen group is about 150MPa.

When broken fabrics were examined first damage was observed near the anvil regions. This caused difficulties in getting correct results in uniaxial tensile testing.

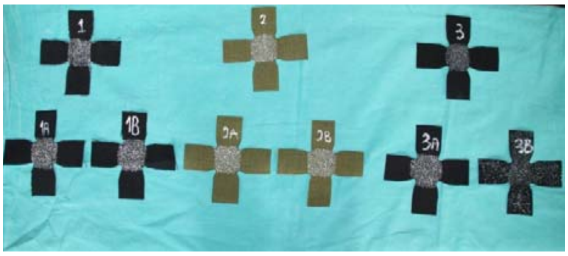

Fig. 2 Fabric Specimens prepared for planar biaxial tensile testing

C. Bulge Test Assembly

This assembly mainly involves in strain-resistant ring design use where the fabric is inflated. The ring is so designed that minimum strain was observed during loading. Total strain was around 0.2 mm under 40 bar pressure. Maximum stress on the steel ring was around 140MPa which provides a maximum safety when the fabrics are tested. The pressurized air is used to inflate and then to burst the fabric. The pressurized air is controlled by 2 manometers. The fabric is gripped by the inner and outer rings and fastened. The test is completed when the fabric bursts. The pressures before and at the instant bursting are recorded.

The fabric specimens tested on pneumatic inflating assembly are as follows:

- Sample 1: Polyurethane coated PA 6.6 fabric
- Sample 2: Uncoated black PA 6.6 fabric
- Sample 3: Polyurethane laminated PA 6.6 fabric
- Sample 4: Airbag PA 6.6 fabric
- Sample 5: Uncoated black PA 6.6 fabric
- Sample 6: Polyurethane laminated PA 6.6 fabric
- Sample 7: Uncoated black PA 6.6 fabric
- Sample 8: Uncoated black PA 6.6 fabric
- Sample 9: Polyurethane laminated PA 6.6 fabric
- Sample 10: Polyurethane coated black PA 6.6 fabric
- Sample 11: Uncoated black PA 6.6 fabric
- Sample 12: Polyurethane coated black PA 6.6 fabric

Fig. 3 Pneumatic Bulge Test Assembly

V. Results

Results obtained from fabric characterizing and all types of tests are presented in the following sections.

A. Type Tests of Fabrics

Results obtained from each type of test have been summarized in the following tables.

TABLE I
PROPERTIES OF FABRICS

	Uncoated Polyamide 6.6	**Laminated Polyamide 6.6**	**Coated Polyamide 6.6**	**Airbag Fabric**
Warp yarn Count	1080 Denier (120 Tex)	1060 Denier (118 Tex)	1080 Denier (120 Tex)	520 Denier (58 Tex)
Weft yarn Count	1100 Denier (123 Tex)	1100 Denier (123 Tex)	1100 Denier (123 Tex)	570 Denier (63 Tex)
Number of warps	14 yarns/cm	16 yarns/cm	14 yarns/cm	19 yarns/cm
Number of wefts	11 yarns /cm	14 yarns /cm	11 yarns /cm	19 yarns /cm
Weight	313 g/m²	404,5 g/m²	368,6 g/m²	230 g/m²
Air permeability	3650 l/dm^2.h	Apparently no leakage	Apparently no leakage	Apparently no leakage

It is seen that the representative fabrics are similar to the structure of an airbag fabric, but are coarser. However, the behavior may be expected as similar.

B. Uniaxial Tests

Results obtained from uniaxial tests have been summarized in the following graphs.

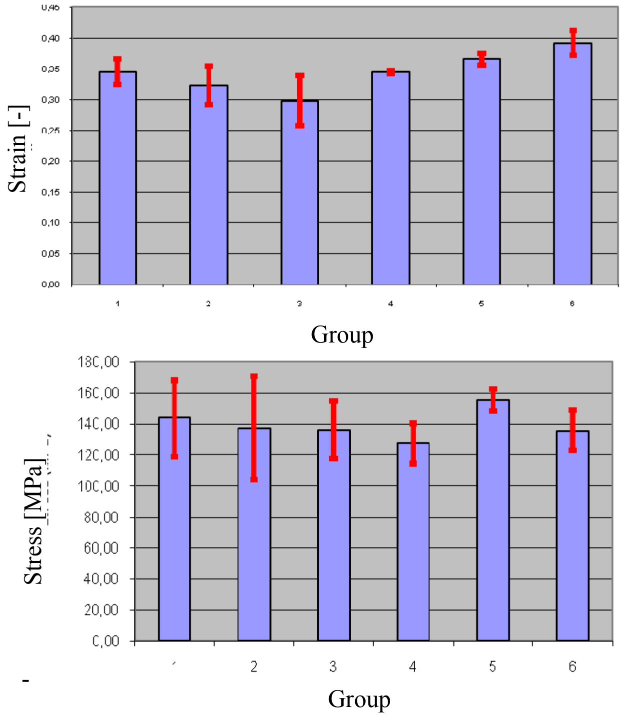

Fig. 4 Stress/Strain Results of Uniaxial Tests at Failure

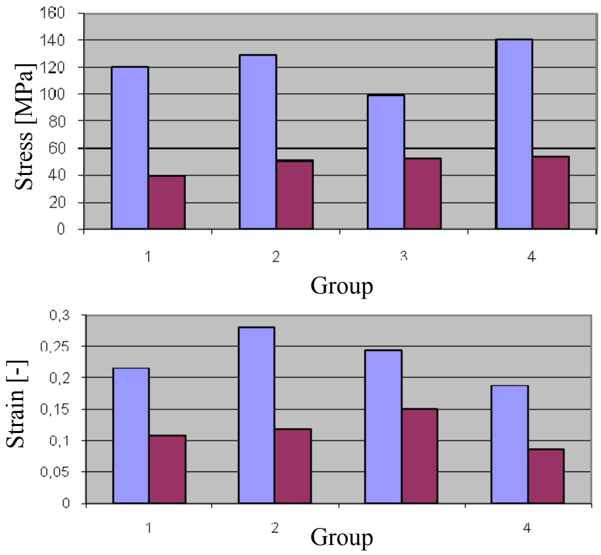

Fig. 5 Stress/Strain Data of Groups of Planar Biaxial Tensile Test

The results of the planar biaxial tensile test yielded inequivalent strain and stress states, though the setup is a kinematically constraint one.

C. Bulge Tests

Results obtained from bulge tests have been summarized in Figure 6-7. Also other test data are plotted for demonstration purposes, to the same scale.

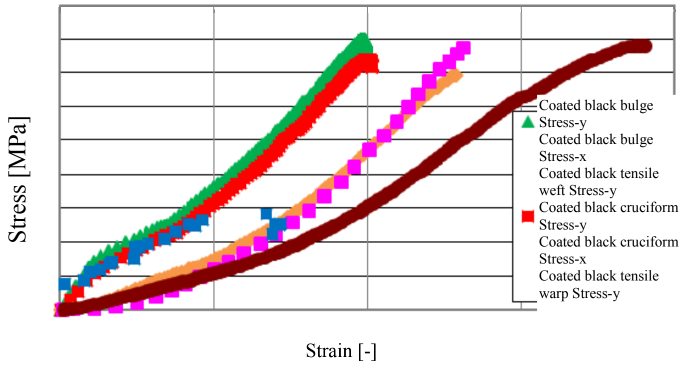

Fig. 6 Stress/Strain Results of Coated Fabric obtained via Various Testing Methods

Maximum stress values in pneumatic bulge testing have increased up to 300MPa while maximum stress values in planar biaxial tensile testing could not exceed 160MPa.

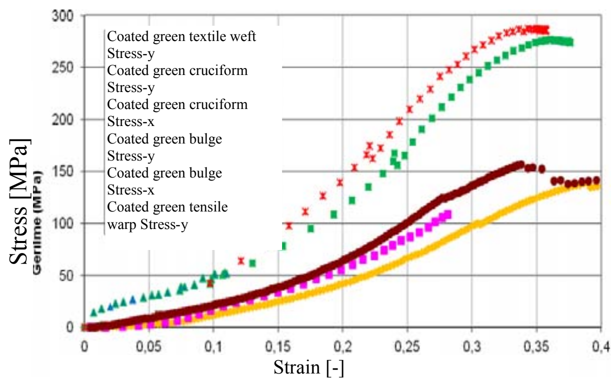

Fig. 7 Stress/Strain Results of Coated Fabric obtained via Various Testing Methods

VI. Conclusion

The most applicable stress behavior against the loading under the real working conditions was obtained by pneumatic inflating test as compared to uniaxial tensile and planar biaxial tensile tests. The samples which have identical properties to airbag fabrics were also used in the present work. Polyamide 6.6 fabrics were chosen as they are mostly used in airbags. Most of the airbags are coated by silicones, polyurethane are used in addition to the membrane laminated polyamide 6.6 It was shown that Polyamide 6.6 fabrics having high biaxial tensile stress are quite suitable to be used in the airbag manufacture.

The data obtained in pneumatic bulge test assembly designed in this paper are compared with the data obtained in uniaxial and planar biaxial tensile testing and it was determined that the values obtained in pneumatic inflating/bursting test assembly were very close to the real behavior of fabric from the point of view of fabric resistance. Moreover, the assembly designed can be used as a base for numerical analysis and modeling of fabric stress parameters. It is seen that the behavior of the material is not similar under bulge and planar biaxial tests. This is possibly due to the fact that for planar test, the filaments are not all being loaded, which is not a realistic assumption.

Further studies may also include:

- Improvements to check the test parameters more precisely by adding the software and hardware to the control of pneumatic valve to better trace the repeatability;

- Improvements to air supply system by electronic control for characterization of damping properties, identifying biaxial viscoelastic behavior and determination of friction properties of fabrics having different constructions based on their yarns types;

- A more secured environment for burst recording with high speed cameras at higher strain rates.

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