(REFEREED RESEARCH)

FINITE ELEMENT MODELING OF RANDOM WASTE COTTON FIBER REINFORCED POLYETHYLENE COMPOSITES

ATIK PAMUK TAKVİYELİ POLİETİLEN KOMPOZİTLERİN SONLU ELEMANLAR MODELLEMESİ

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Received: 26.12.2011 Accepted: 07.11.2012

ABSTRACT

This paper presents a procedure for developing a finite element model of random chopped cotton fiber reinforced polyethylene composites to determine their mechanical properties. In experimental studies, composite plates with polymer (polyethylene) matrix and waste cotton fabrics reinforcements were manufactured in two different volume fractions (7.5% and 15%) by custom made extrusion technique. Some of the produced plates granulated down to the size enough to use in extrusion process and used again for plate production. These processes were repeated at most 6 times. Each processed material was subjected to uniaxial tensile experiments and stress-strain curves were obtained. In the finite elements analysis step, a unit cell model was developed and analyzed by ANSYS to obtain the effectiveness of reinforcements and fiber orientation, according to volume fraction. Finite element analysis results were compared to experimental test results and also effectiveness of fibers are investigated by the use of range of strain energy. It has been observed that by increasing the volume fraction of the reinforcement material, mechanical properties such as strength has been improved.

Key Words: Textile composites, Cotton fiber, Recycle, Finite Element Analysis (FEA).

ÖZET

Bu makalede rastgele kesilmiş pamuk lif takviyeli polietilen kompozitlerin sonlu elemanlarla modellenmesi üzerine bir yöntem sunulmaktadır. Kompozit plakalar, polimer (polietilen) matris ve atık pamuk kumaş takviyeden iki farklı hacimsel oranla (%7,5 ve % 15) özel yapım ekstrüzyon makinası kullanarak imal edilmiştir. Bazı plakalar tekrar parçalanarak granül hale getirilmiş ve tekrar imal edilmiştir. Bu işlem en fazla 6 defa tekrar edilmiştir. Her bir işlem sonrasında imal edilen plakaların tek eksenli gerilme deneyleri yapılmış ve gerilme-uzama eğrileri çıkarılmıştır. Sonlu elemanlar aşamasında ise birim hücre modeli ğeliştirilerek, ANSYS programı ile hacimsel oranlara göre takviye ve lif yönlenmesi analiz edilmiştir. Sonlu elemanlar analizi deneysel sonuçlarla kıyaslanmış bunun yanında uzama enerjisi miktarına göre elyaf yerleşiminin etkisi de analiz edilmiştir. Takviye miktarının hacimsel oranının arttırılması ile malzemenin mukavemet gibi mekanik özelliğinin de arttığı gözlemlenmiştir.

Anahtar Kelimeler: Tekstil kompozitleri, Pamuk lifi, Geri dönüşüm, Sonlu Elemanlar Analizi

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1. INTRODUCTION

In nowadays technology, traditional materials can not provide all necessities anymore. With the progress of technology, and parallel to this the progress of material technology impels the producers and researchers to search new materials or improving existing materials.

Textile composites represent a variety of composite materials produced by polymer composite materials with textile reinforcements. The attention on composite materials with thermoplastic matrixes gradually increases because of some advantages. These are, high volume process ability, recyclability, superior damage tolerance and fracture toughness, and ability to produce complex shapes. Predictive process and material characterization tools are much needed in industry to minimize expensive tooling/process trials and to improve the design avenues for parts (1).

Despite the complexities of the methods, the three-dimensional (3D) finite element model of the unit cell approach is the most popular method to estimate the elastic and failure behavior of textile composite materials. In this method, the 3D finite element model is utilized with orthotropic textile structure and isotropic matrix material properties. The first application of this approach was recognized by Whitcomb (2) and, Guedes and Kikuchi (3). The application continues to be used in subsequent studies (4, 5, 6), with thermal expansion using unit cell with elastic moduli and coefficients.

In the modeling approaches that attempt to model the fiber architecture, a typical representative (or repeating) volume element (RVE), sometimes called a unit cell, is considered, and suitable boundary conditions are assumed at its edges so that the behavior of this element can be extrapolated to that of a continuous composite sheet (7). Besides, numerous approaches using different Poisson's ratios are in use (8, 9, 10, 11). Lomov *et al.,* used a special finite element analysis software, to further simplify it (12).

On analyzing textile structure, some nonlinearities causing poor mechanical behaviors are observed. Enrico D. Amato (13) revealed the importance of nonlinear effects mainly caused by a variation in the waving of the fibers under loading.

Our study presents a procedure to develop a finite element model of random waste cotton fiber reinforced polyethylene composites, to determine their mechanical properties. Finite element analysis results are compared with experimental test results. Useful information for material design like the immeasurable load sharing between phases, the strength between phases and load levels of the failure of phases are examined.

2. MATERIAL AND METHOD

2.1. Material

The materials used in this study are waste cotton fabric and LDPE (Low density polyethylene). In Figure 1 and Figure 2 the composite granules and the internal structure of the composite material after the repetitive granulating operations are shown. Also the chief physical and mechanical properties of the LDPE are shown in Table 1.

Table 1. Typical properties of LDPE (14)

Property	Low Density Polyethylene
Tensile Strength (MPa)	8-12
Tensile Modulus (MPa)	200-400
Elongation at Break (%)	600-650

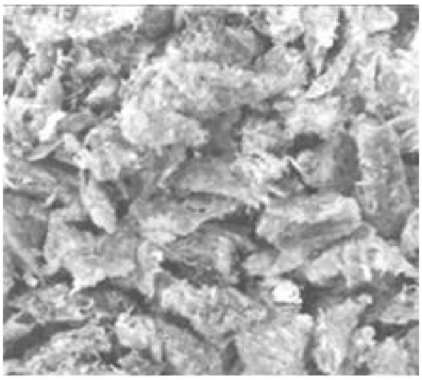


Figure 1. Composite granules picture

2.2. Method

Two different waste cotton fabric reinforced polyethylene composites were manufactured in 7.5% (Model I) and 15% (Model II) volume fraction by the extrusion technique.

Extrusion is a high volume manufacturing process in which raw plastic material is melted and formed into a continuous profile. The LDPE granules and waste cotton fabrics are gravity fed from a top mounted hopper into the barrel of the extruder. With the heat of the barrel and the pressure of the screw, the molten composite material pass through a head and under rollers and then composite plates are pressed and cooled in hydraulic press for 20 minutes. Some of the produced plates granulated down to the size enough to use in extrusion process and used again for plate production. These processes were repeated at most 6 times.

Each processed material specimens were subjected to uniaxial tensile test according to ASTM D638-08. Next, the results obtained for a set of three test samples were processed and the effectiveness of volume fraction were investigated.

All available experimental data clearly show that the materials considered are characterized by a clearly nonlinear behavior (Figure 3).

Experimental results reveal that increasing the volume fraction improves the mechanical properties such as strength characteristics and for the same volume fraction, the extrusion direction composites have better strength for the same strain values (Figure 3).

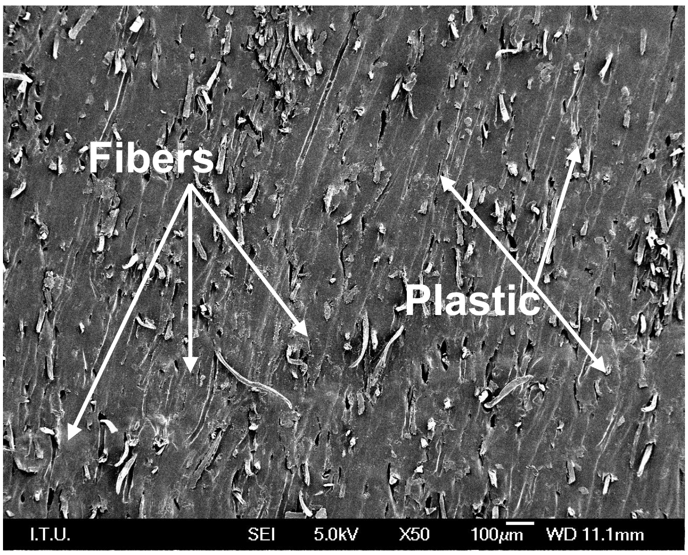
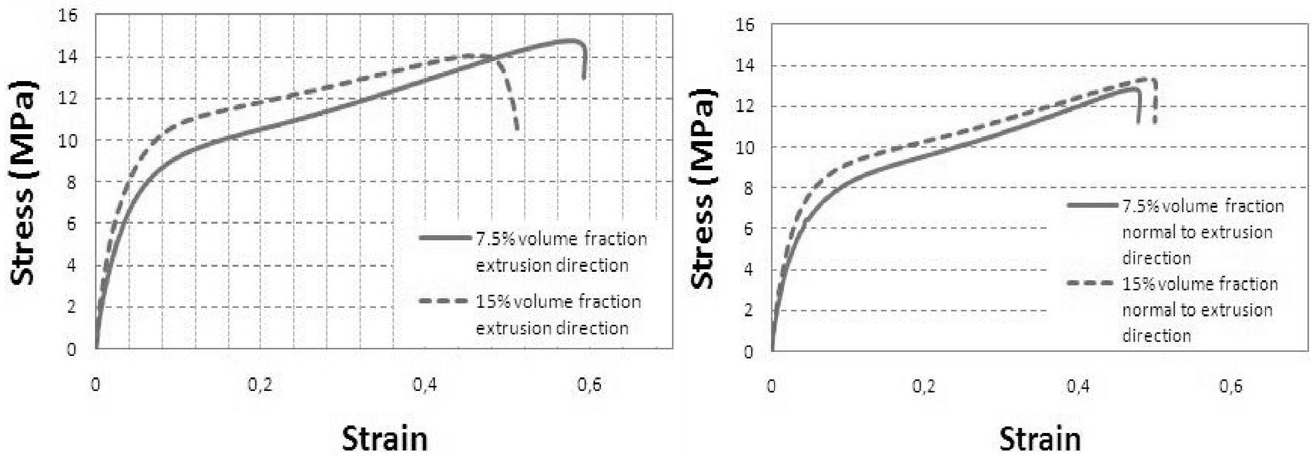


Figure 2. Internal structure of composite material (fibers and plastic)



(a) (b)

Figure 3. Stress-strain curves of 7.5% and 15% reinforced composites at a) extrusion direction and b) at normal to extrusion direction

3. RESULTS AND DISCUSSIONS

The 3D finite element (FE) analysis is an alternative method to the experiments to determine the uniaxial tensile test behavior. This reveals the material properties used by a unit cell or the representative volume elements (RVE) that represent the whole composite structure.

To understand the composite structure stereo-optic microscope and SEM photos are used. At first cotton fabrics and LDPE granules are used in composite plates. Then, after the granulating operations fabrics are seperated into yarns and fibers. In Figure 4, the orientation of the yarns and fibers in extrusion direction is shown. Due to the glossy finish of the polymer matrix surface, it is very hard to get clear image, given figure is the best view as possible.

After the third granulating operation, composite plates contain yarns and fibers (Figure 5). The homogenization of the only fibers is provided in sixth operation (Figure 5). The cross-section of the cotton fiber is eliptical shaped and the dimensions are measured with SEM (Figure 6). The fibers are found in composite plates randomly. Therefore using the optical image in Figure 7, the fibers are modeled in the same coordinates and same dimensions as laminates (Figure 8). 9 composite laminates are mixed together and 4 composite representative volume elements for Model I and II volume fractions are obtained (Figure 9 and Figure 10). 2-D layers which are obtained from optical images, are merged with other layers in different orientation to obtain more realistic 3-D modeling.

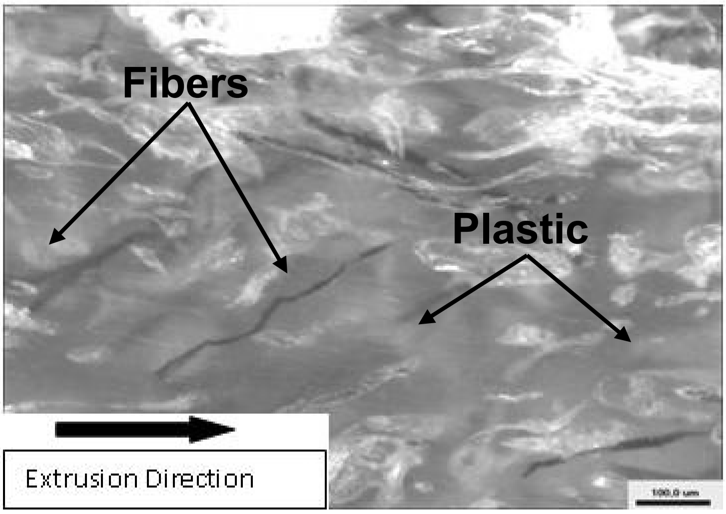
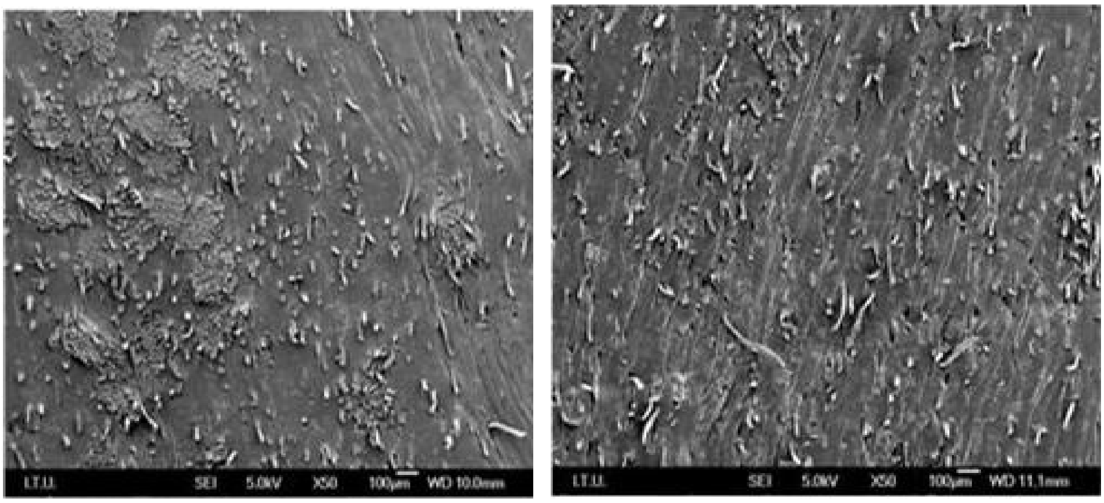


Figure 4. The orientation of the yarns and fibers in plastic



a b

Figure 5. (a) Composite plates after the third granulating operation and (b) the homogenization of fibers after the sixth granulating operation

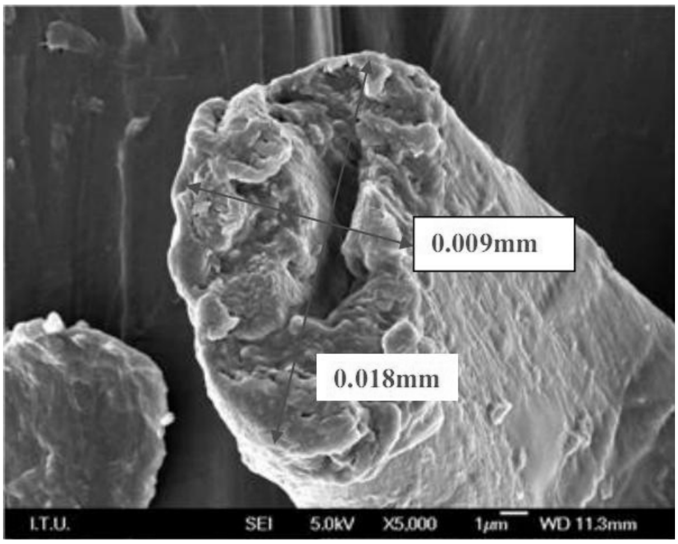
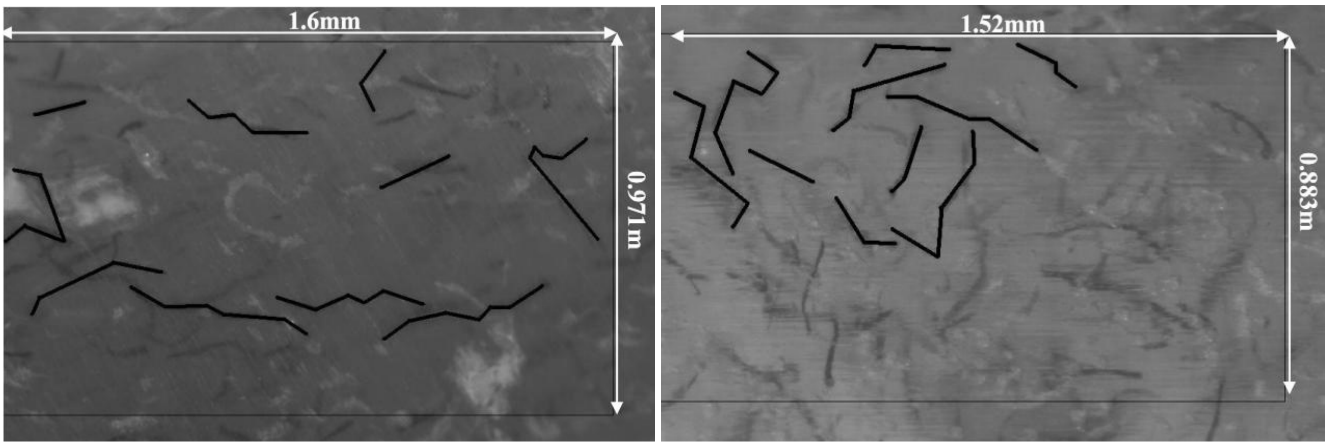


Figure 6. The eliptical shaped cross-section of the cotton fiber with dimensions



a b

Figure 7. (a) The microscope photo of 7.5% reinforced composite and (b) the microscope photo of 15% reinforced composite

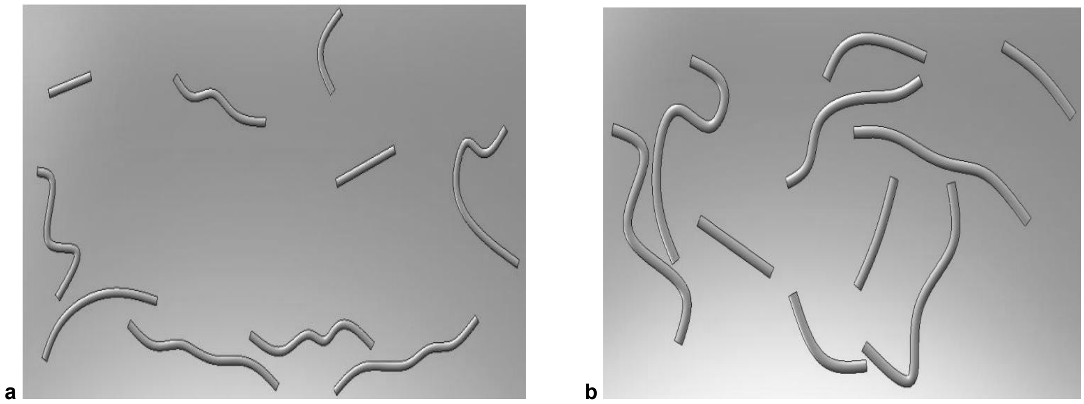


Figure 8. (a) Modelling of 7.5% reinforced composite's fibers and (b) modelling of 15% reinforced composite's fibers

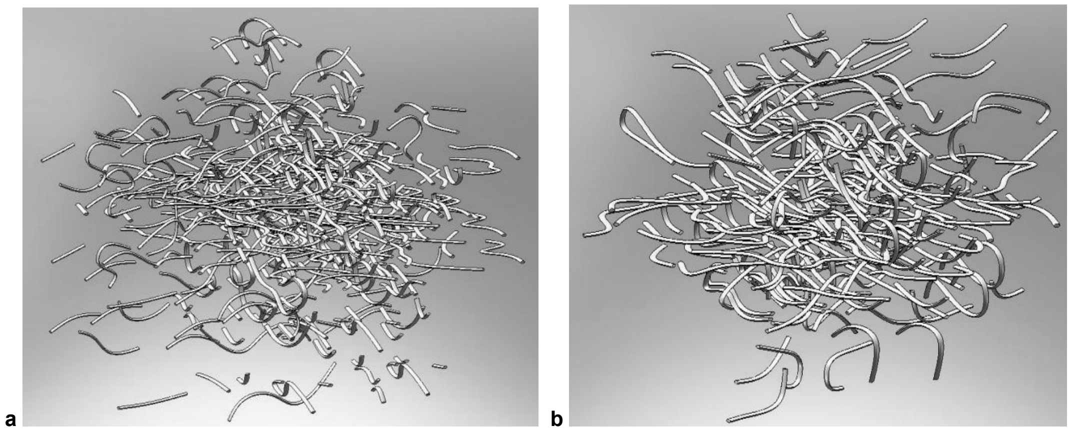


Figure 9. (a) 7.5% reinforced composite's mixed laminates and (b) 15% reinforced composite's mixed laminates

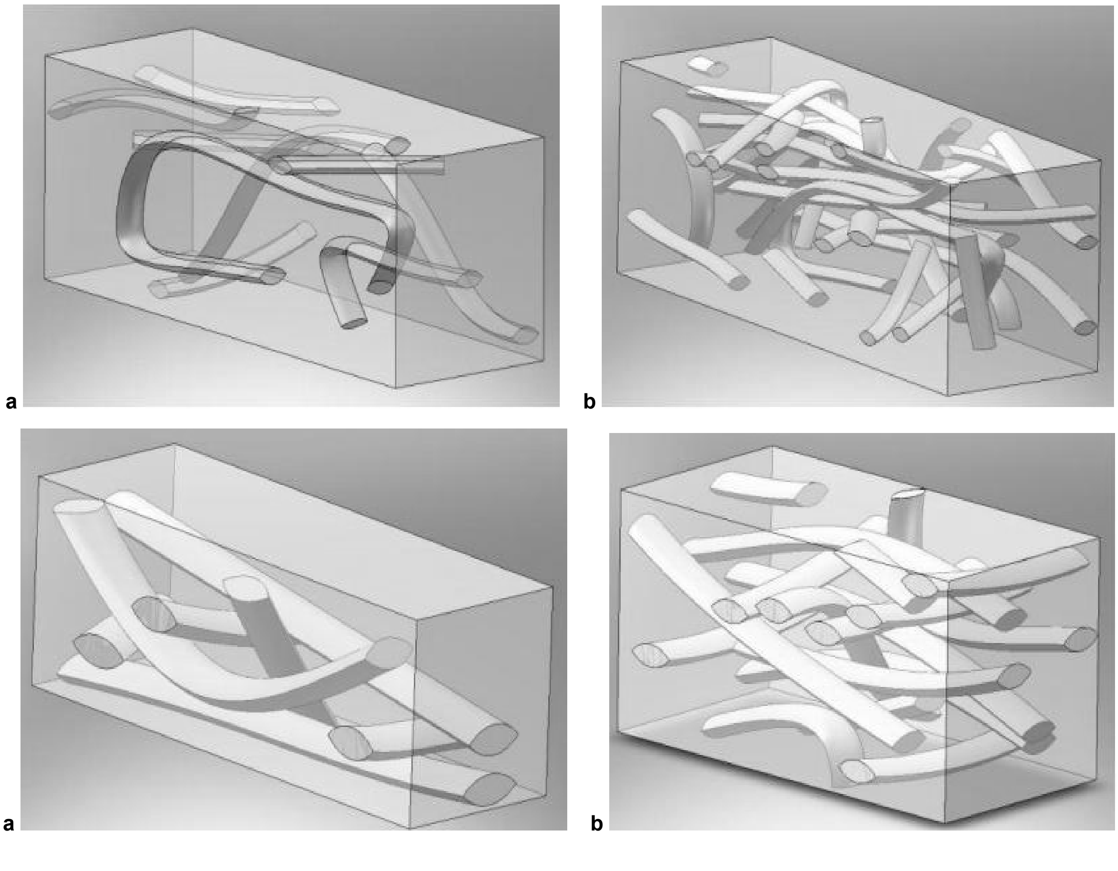


Figure 10. (a) 7.5% reinforced composite 1. FE Model, (b) 7.5% reinforced composite 2. FE Model, (c) 15% reinforced composite 1. FE Model and (d) 15% reinforced composite 2. FE Model

Finite element analysis of textile composite materials consist of CAD (computer aided design) and finite element analysis parts. Due to the difficulties of CAD modeling in ANSYS software, the geometry of the fibers is modeled using SOLIDWORKS software in the CAD part and saved in IGES file format before importing. Then the data of 3D fiber models is imported to ANSYS software for finite element analysis, as shown in Figure 11. As the same procedure is used for all the composites, 7.5% reinforced second textile composite model is shown as an example.

After importing the fibers' data, a matrix pocket is created by subtracting the fiber volumes from a rectangular block, which aptly meets the 7.5% and 15% volume fractions.

In this study, a 3D structure element SOLID186 of ANSYS is used for the entire model (11). The element used is a 3D 20-node (three degrees of freedom per node) structural solid element (11). It has quadratic displacement behavior and is recommended for modeling irregular meshes (11).

Two material models are used for the analysis. For the reinforcement material, hyper-elastic model is used. Relatively low elastic modules, and high volumetric elastic modules with large volumes of material exposure to changes in the nature of this material, indicates hyper-elastic behavior. As evident from Figure 12, the yarns and the fibers of the fabrics exhibit nonlinear behavior. As the data of the uniaxial tensile test of yarns alone is available, the Neo-Heokan hyper-elastic material model, which gives proximate results to the uniaxial tensile test data, is used to obtain the coefficients for this model by employing the curve fitting tool of ANSYS. For the matrix material, the Multilinear Isotropic Hardening material model is used because it is suitable for the thermo-plastic materials and the high deformation ratios. The uniaxial test data of LDPE after the 6 granulating operations is used for curve fitting tool of ANSYS. The elasticity module is 192.33 MPa and the poisson ratio is 0.49. Then, according to the boundary conditions of the uniaxial tensile test finite element analysis is simulated in 30 load substeps.

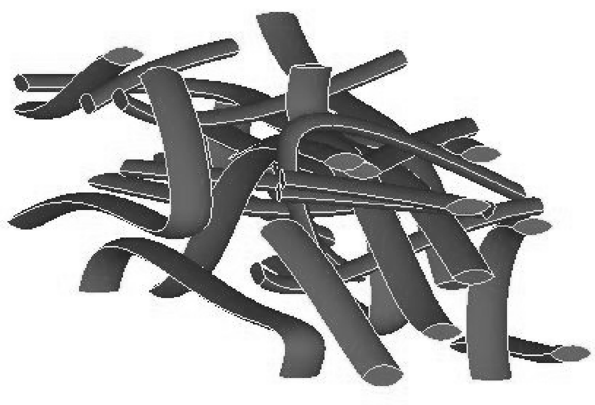


Figure 11. The geometric model of the fibers

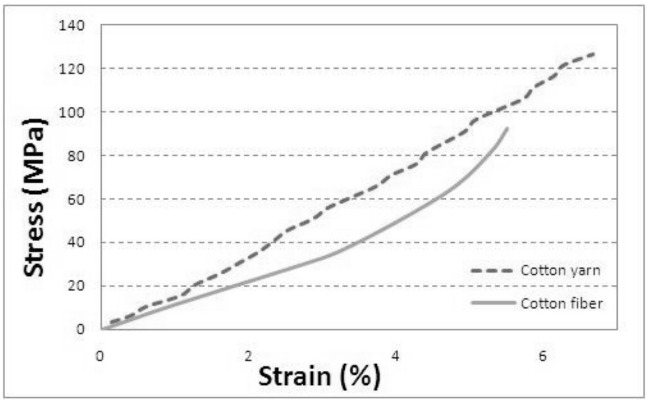


Figure 12. Stres-strain curves of cotton yarn and fibers

3.1. Strain analysis

As evident from the experimental data Figure 2 and Figure 3, textile composite materials exhibit non-linear stress-strain behavior. Using the nonlinear finite element analysis, non-linear stress-strain curves were obtained.

In the nonlinear finite element analysis, the strain and stress results obtained were evaluated for the experimental data accrued from different volume fractions. For example, some results are listed in Figure 13 and Figure 14.

In Figure 13 and Figure 14, for the same strains (~0.013) and (~0.06), the stress values obtained from the nonlinear finite element analysis are above the experimental results. Because of the potential voids in structure, fiber diffraction and matrix-fiber debonding problems, the analysis results are less ductile than experimental results.

In both results for different volume fractions, the second finite element models'results are closer to the experimental results.

3.2. Strain energy analysis

In composite materials, the load capacity of the reinforcement within the reinforcement volume fraction is observed to indicate the effectiveness of the reinforcement.

In a 20% reinforced composite material, if the reinforcements of the material carry 20% load that causes the elastic strain, the effectiveness of reinforcement can be said to be 100%.

Nonlinear finite element analysis is simulated in 30 load substeps to obtain optimum results without analysis errors. Strain energy values per volume (reinforcements and matrix) are shown in Table 2.

As evident from Table 2, increasing the volume fraction of reinforcements, increases the effectiveness of the reinforcement.

The effectiveness of reinforcements increases in the direction of extrusion. Because of the orientation, in extrusion direction, the reinforcements carry 3 times of volume fraction, in normal to extrusion direction, the reinforcements carry 2 times of volume fraction.

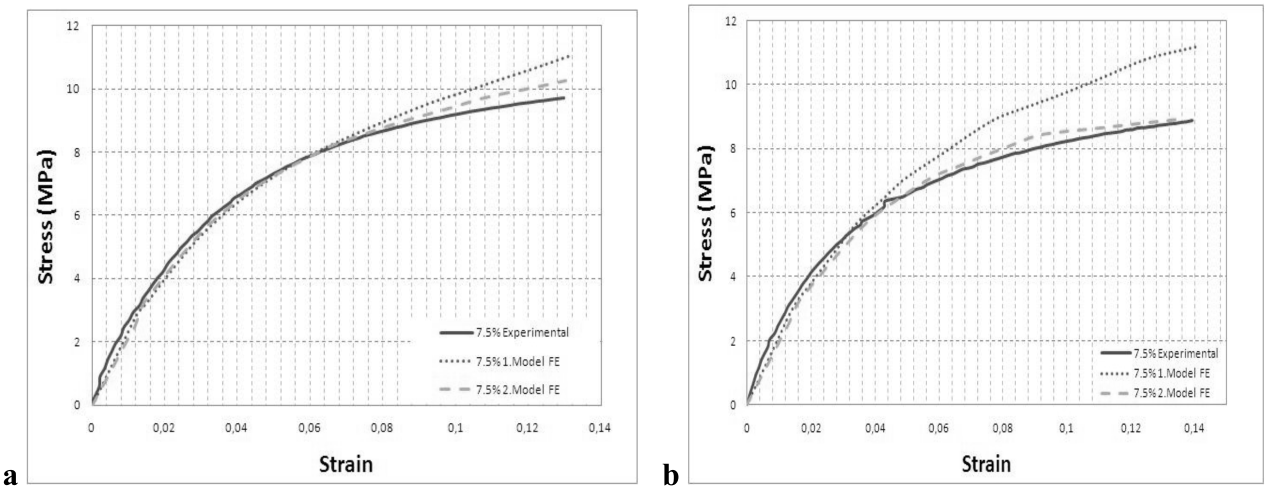


Figure 13. Comparative finite element analysis and experiment results. (a) 7.5% reinforced composite at extrusion direction and (b) 7.5% reinforced composite at normal to extrusion direction

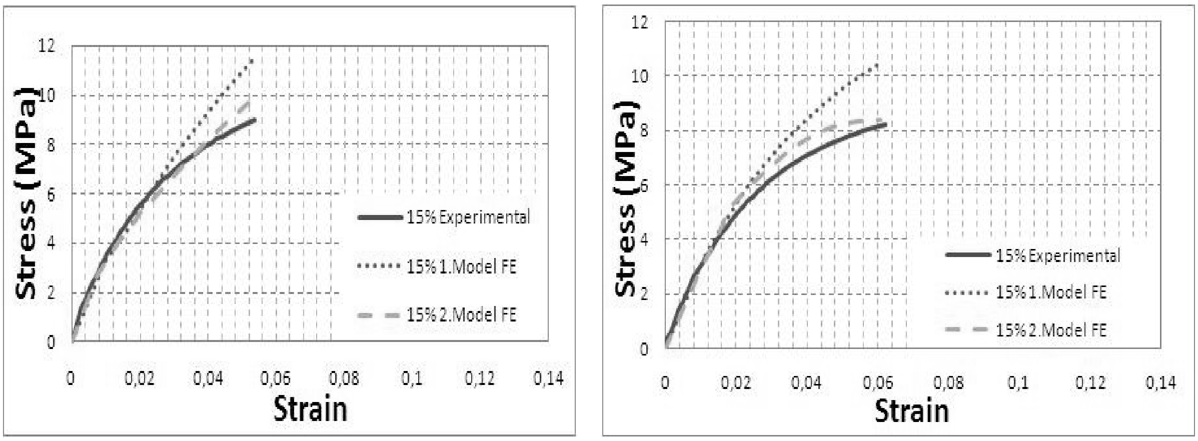


Figure 14. Comparative finite element analysis and experiment results. (a) 15% reinforced composite at extrusion direction and (b) 15% reinforced composite at normal to extrusion direction

Table 2. Strain energy per volume of composite material models

F.E. Model	Strain energy per volume (%)				
	Tension Direction	Volume Fraction (%)		Partial Energy (%) (FEA)	
		Reinforcement	Matrix	Reinforcement	Matrix
1. Model	0°	7.5	92.5	20.5	79.5
1. Model	90°	7.5	92.5	12.5	87.5
2. Model	0°	7.5	92.5	24.7	75.3
2. Model	90°	7.5	92.5	17.7	82.3
1. Model	0°	15	85	47.8	52.2
1. Model	90°	15	85	33.3	66.7
2. Model	0°	15	85	41.6	58.4
2. Model	90°	15	85	34.3	65.7

0°= extrusion direction; 90°= orthogonal to extrusion direction

4. CONCLUSIONS

A procedure is developed for the finite element model of random chopped cotton fiber reinforced poly-ethylene composites to determine their mechanical properties. Experiments and nonlinear finite element analysis were performed to obtain the stress-strain curves and to thus determine the effectiveness of the reinforcements. The results of this study can be summarized as follows:

- For 7.5% and 15% volume fractions the second finite element models' with more fibers results are closer to the experimental results.
- The balance of the finite element results and experimental results is conserved in extrusion direction more than the normal to extrusion direction. In extrusion direction load

is applied paralel to the fibers. But in normal to extrusion direction load is applied vertical to the fibers. Reinforcement-matrix debonding appears in fibers which are vertical to the load.

- The orientation of the fibers in composite material affect the effectiveness of the reinforcements.
- In extrusion direction, the reinforcements carry load as 3 times of volume fraction, in normal to extrusion direction, the reinforcements carry load as 2 times of volume fraction.
- Increasing the volume fraction of the reinforcements, increases the effectiveness of the reinforcement and in extrusion direction, the effectiveness values show better results.
- With more actual photos and finite element models, better results can certainly be obtained in future works.

This research is supported by TUBITAK, Project no:107M354.

REFERENCES

1. Vaidya UK, Chawla KK, Thattaiparthasarthy K. Balaji, and Goel A. The Process and Microstructure Modeling of Long-Fiber Thermoplastic Composites. 2008.
2. Whitcomb JD. Three-dimensional stress analysis of plain weave composites. Composite Materials: Fatigue and Stresses (3rd volume), A92–39001, 1990. p. 16–39
3. Guedes JM, Kikuchi N. Preprocessing and postprocessing for materials based on the homogenization method with adaptive finite element methods. Computer Method in Applied Mechanics and Engineering, 1990. p. 143–198.
4. Chapman C. and Whitcomb J. Effect of assumed tow architecture on predicted moduli and stresses in plain weave composites. J. Composite Materials, 1995 29(16). p.2134–2159.
5. Ng SP, Tse PC, Lau KJ. Numerical and experimental determination of inplane elastic properties of 2/2 twill weave fabric composites. Composites Part B, 1998 29B. p.735–744.
6. Dasgupta A. Agarwal RK and Bhandarkar SM. Three-dimensional modelling of woven-fabric composites for effective thermo-mechanical and thermal properties. Composites Science and Technology, 1996 56. p. 209–223.
7. Jones IA, Pickett AK. Mechanical properties of textile composites. Design and Manufacture of Textile Composites. Cambridge, 2005. p. 255–292
8. Karkkainen RL, Sankar BV. A direct micromechanics method for analysis of failure initiation of plain weave textile composites. Compos Science and Technology 66: 2006. p. 137–150.
9. Kim HJ. Swan CC. Voxel-based meshing and unit-cell analysis of textile composites. International Journal for Numerical Methods in Engineering 56: 2003. p. 977–1006.
10. Lomov SV, Belov EB. Bischoff T et al. Carbon composites based on multiaxial multiply stitched preforms. Part I - Geometry of the preform. Composites Part A 33 2002. p. 1171–1183.
11. Takano N, Uetsuji Y, Kashiwagi Y, Zako M. Hierarchical modelling of textile composite materials and structures by the homogenization method. Modelling and Simulation in Materials Science and Engineering 7: 1999. p. 207–231.
12. Lomov SV, Ivanov DS, Verpoest I, Zako M, Kurashiki T, Nakai H, Hirosawa S. Meso-FE Modelling of Textile Composites: Road map, data flow and algorithms. Composites Science and Technology 67 2007. p. 1870–1891.
13. D'Amato E. Nonlinearities in mechanical behavior of textile composites. Composite Structures 71 2005. p. 61–67.
14. http://www.matbase.com/material/polymers/commodity/ldpe/properties, downloaded on 12/08/2012.