International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:6, 2015

Simulation of Non-Crimp 3D Orthogonal Carbon Fabric Composite for Aerospace Applications Using Finite Element Method

Sh. Minapoor, S. Ajeli, M. Javadi Toghchi

Abstract**—**Non-crimp 3D orthogonal fabric composite is one of the textile-based composite materials that are rapidly developing light-weight engineering materials. The present paper focuses on geometric and micromechanical modeling of non-crimp 3D orthogonal carbon fabric and composites reinforced with it for aerospace applications. In this research meso-finite element (FE) modeling employs for stress analysis in different load conditions. Since mechanical testing of expensive textile carbon composites with specific application isn't affordable, simulation composite in a virtual environment is a helpful way to investigate its mechanical properties in different conditions.

Keywords**—**3D orthogonal woven composite, Aerospace applications, Finite element method, Mechanical properties.

I. Introduction

THE drive within the aerospace composites field over the last decade has been to reduce cost, increase component performance and reduce component weight. Composites have now gained an accepted position in aircraft design, while carbon fiber reinforced materials have become the mainstay of secondary components such as wing movables (flaps, spoilers, rudder, etc.) and have found their way into primary structural components such as complete horizontal stabilizer and vertical stabilizer structures [1].

In an attempt to overcome many of the problems with the manufacturing and mechanical properties of polymer laminates reinforced with a two-dimensional (2D) layered fiber structure, considerable attention has been given to the development of advanced polymer composites reinforced with Three-dimensional (3D) fiber architectures. Most attention has been given to 3D composites manufactured by the textile techniques of weaving, braiding, stitching and knitting [2].

Pioneered by aerospace companies such as General Electric, the non-crimp 3D orthogonal fabric technology was developed further by Fiber Materials Incorporated [3]. 3D orthogonal woven composites have been widely applied to structure engineering owing to the high stiffness and strength along in-plane directions and thickness directions. The non-crimp feature of yarns in 3D orthogonal woven fabric leads the highest Young's modulus and stress wave propagation velocity compared with other textile preforms. Compared to laminated composites and other 3D textile structural composites, 3D orthogonal woven composite has been recognized as more competitive because of its higher stiffness and strength in three orthogonal directions. The 3D orthogonal woven composite allows the tailoring of properties for specific applications and shows better delamination resistance and damage tolerance, especially in thickness direction [4].

This paper will investigate the mechanical properties and heat transfer of non-crimp 3D orthogonal carbon fabric composite since the other widely used composite reinforcement fibers in aerospace applications. A unit cell model of the 3D orthogonal woven composite has been developed to investigate its mechanical and thermal behavior in different load conditions. Finite element software (ABAQUS version 11) is used to analysis stress and heat transfer of the non-crimp 3D orthogonal carbon fabric composite.

II. Non-Crimp 3D Orthogonal Fabrics

By nature of the described 3D weaving process, a *no-crimp* fabric is produced, which means that all warp- and fill-directional yarns remain practically straight. This feature immediately distinguishes this kind of fabric from conventional 2D woven fabrics which are crimped due to all warp- and weft-directional yarns interlaced. Note that crimp is also present in some other types of 3D woven fabrics [5].

Khokar named this kind of fabrics as NOO Bed fabrics, which is an acronym for Non-interlacing, Orthogonally Orientating and Binding. These fabrics are different in structure compared to the classical weaving ones. There are three different yarns positioned in three coordinates (x, y, and z). However, the yarns are not interlaced with each other as in the conventional weaving [6]. Noobing is a non-woven 3D fabric-forming process that essentially assembles three mutually perpendicular sets of yarns. There is no interlacing (as with weaving), interlooping (as with knitting) or intertwining (as with braiding) of the involved yarns. Fig. 1 represents non-crimp 3D orthogonal fabric's structure. Orthogonal fabrics are divided into two groups as uniaxial and multiaxial. Having a no-crimp fabric as composite reinforcement is obviously beneficial, because significantly higher in-plane stiffness and strength can be achieved [7].

Sh. Minapoor is Ph.D Student at Department of Textile Engineering, Isfahan University of Technology, Isfahan 84156-83111, IRAN (phone: +98 31 33915039; fax: +98 31 33912444; e-mail: shohreh.minapoor@tx.iut.ac.ir).
S. Ajeli is Associate Professor at Department of Textile Engineering, Isfahan University of Technology, Isfahan 84156-83111, IRAN (e-mail: sajeli@cc.iut.ac.ir).
M. Javadi Toghchi is Ph.D Student at Department of Textile Engineering, Amirkabir University of Technology, Tehran, IRAN (e-mail: m_javadi86@yahoo.com).

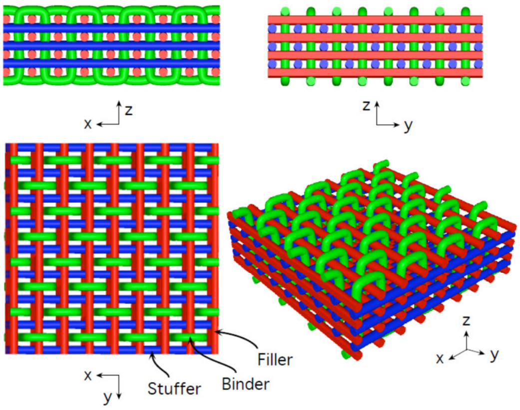


Fig. 1 A noobed fabric seen from its three principle planes and from an isometric view [7]

Since the 1970's a wide range of processes have been developed to produce 3D orthogonal pre forms. These vary from techniques utilizing relatively conventional weaving mechanisms but with multiple weft insertion, to processes that have very little in common with the traditional weaving process. Some of the earliest work in 3D orthogonal nonwovens was pioneered in France by Aerospatiale and Brochier who licensed their separately developed technology in the USA to Hercules and Avco Specialty Materials respectively. Significant development of machinery to manufacture 3D non-woven pre forms has also been undertaken within Japan since the 1970's, particularly at the Three-D Composites Research Corporation (a subsidiary of the Mitsubishi Electric Corporation). Method for the production of non-woven pre forms have been developed by Fukuta et al. is shown in Fig. 2. Again these processes rely upon the insertion of yam or cured composite rods along pre-set directions, the main difference between these methods and others, are the mechanisms to control that insertion [8].

By developing production methods of non-crimp 3D orthogonal fabrics, researchers have focused on studying of mechanical properties and modeling of this structure. Some research was done on own fabric and the other analysis composite reinforced with this fabric. An analytical model was proposed to calculate the energy absorption of the 3 non-crimp 3D orthogonal fabric under ballistic penetration of a hemispherical-cylindrical rigid projectil by Shi et al. They have expressed the non-crimp features of warp and weft yarns impart the highest energy absorptions to 3D orthogonal woven fabric than other kinds of 3D woven fabrics under ballistic impact and there are greater potential applications of the in ballistic protection [9]. Deformability of a single-ply E-glass non-crimp 3D orthogonal woven reinforcement is experimentally investigated by Carvelli et al. This study is focused on the understanding and measurement of the main deformation modes, tension and in plane shear, which are involved during draping of composite reinforcements by uniaxial and biaxial tension; in-plane shear investigation using uniaxial bias extension and picture frame tests; and measurements of the fabric thickness variation during shear [10]. The ballistic impact damages of 3D orthogonal woven fabric penetrated under a conically cylindrical rigid projectile were investigated from experimental tests and finite element simulations by Jia et al. In this research a microstructure model of the non-crimp 3D orthogonal fabric was established and imported into finite element geometrical preprocessor [11]. Mishra et al. have focused on geometric and micromechanical modeling of 3D orthogonal fabrics for composite applications and employs meso-finite element (FE) modeling for it. Analysis is done on unit cell instead of full fabric in ANSYS [12].

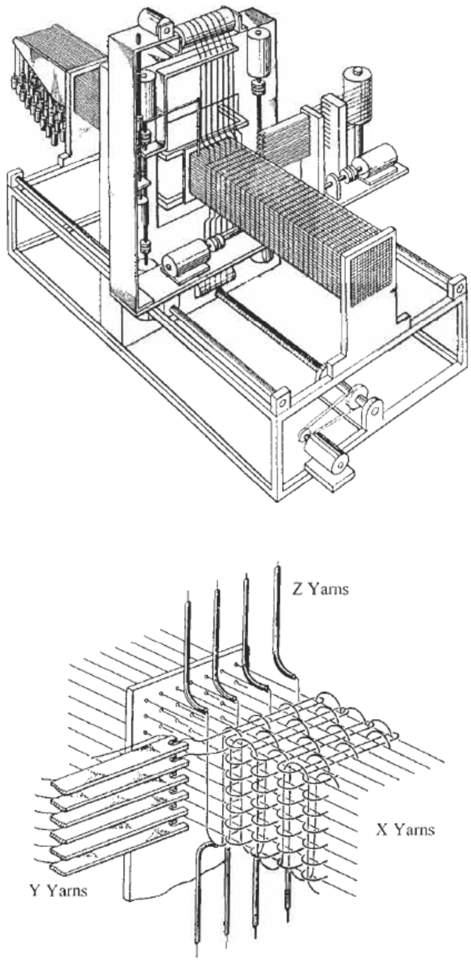


Fig. 2 Illustration of Fukuta's et al. equipment for the manufacture of 3D non-woven preforms [8]

Research and modeling of the mechanical properties of composite reinforced with non-crimp 3D orthogonal fabric were often analyzed failure mechanisms and damage. Analytical and finite element models to predict the mechanical properties and fracture resistance of these composites were presented [13]-[15].

III. Finite Element Method

Finite Element Method (FEM) is a numerical method that has been used for physical problem analysis with differential equation or energy theorem. This method is used for problems with complex geometry, boundary conditions and equations which don't permit analytical solution of system. So, numerically methods are used in these cases and finite element method is one of these methods. According to this definition and structure complexity in textiles, it looks application of this method in analysis of textiles conclude realistic and more ideal results [16], [17].

ABAQUS is one of the strongest and most reliable finite element softwares which have special position for researchers in industry and academics. Compared with finite element softwares, possibility of solution in explicit and implicit methods, nonlinear analysis such as plastic behavior and large deformations and easy user accessibility to sub-programs are the most important characterizes of this software.

IV. Method of Modeling

In this article finite element software (ABAQUS version 11) is used for simulating the non-crimp 3D orthogonal carbon fabric.

A. Geometry and Material Property of 3D Fabric

In order to estimate non-crimp 3D orthogonal carbon fabric in different loading conditions, the geometry of fabric should be determined. The dimension of fabric in this study is considered 10*10*10 mm^3 with carbon fiber 12k and the fabric has been analyzed in this structure. As regards the structure of the fabric is Three-D and also solid, the geometry of elements should be considered as 3D solid. So for that carbon fiber with 10mm length is selected and after that the properties of carbon 12k is assigned to each of them. The properties of fiber are shown in Table I. Finally carbon fiber due to its considerable dimensions was assembled and generates non-crimp 3D orthogonal carbon fabric which is shown in Fig. 3.

TABLE I
Properties of Carbon Fibers [18]

Type	Young's Modulus *(10^9 N/M^2)*	Density *(g/cm^3)*	Poisson's Ratio	Thermal conductivity *(W/m-K)*
T300/12K	230	1.76	0.27	300

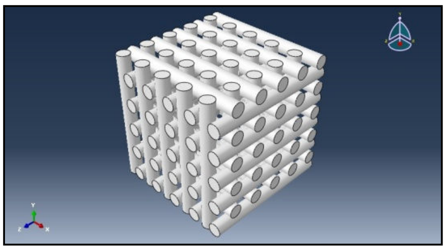


Fig. 3 Simulation of non-crimp 3D orthogonal carbon fabric in ABAQUS

B. Analysis Steps

After specifying the geometry and properties of fabric, we should specify the type of analysis base on loading conditions. In this study three different types of analysis have been used base upon loading conditions. To analyze the behavior of non-crimp 3D orthogonal carbon fabric under tensile and compressive forces, Dynamic explicit method has been used. In this method the resolvation time has been considered 0.1 s and in this period the convergence of answer was obtained. Also for analyzing the behavior of non-crimp 3D orthogonal carbon fabric under torsion and flexural torque, static riks method has been used. This method helps to increase convergence rate in ill conditions. So riks method has been used in evaluating the post-buckling of solid elastic rod. For evaluating the amount of heat transferred of fabric, static riks method has been used in steady state. Before choosing a specific type of analysis, should noticed that all analysis have to be done in non-linear geometry conditions. The reasons of this matter are:

i. big varies mean of deviation or rotation or high deformation
ii. properties of materials means of non-linear elasticity, plasticity or rapture
iii. boundary conditions means of friction between levels

C. Boundary Condition and Loading

For analyzing the behavior of non-crimp 3D orthogonal carbon fabric, boundary conditions should be defined that one face is fully fixed without any freedom of movement and also force is applied to the front face. These boundary conditions in all mechanical analysis in this study have been assumed same and constant, so as to compare behavior in each different condition. After defining the type of analyze and also boundary conditions, the type and quantities of applying force determine. Fig. 4 shows a structure of non-crimp 3D orthogonal carbon fabric simulated in ABAQUS software under tensile force.

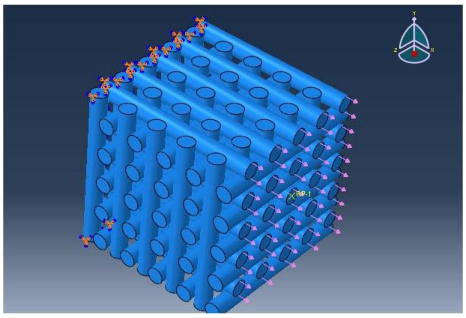


Fig. 4 Tensile load applied to one face of non-crimp 3D orthogonal carbon fabric model in ABAQUS

D. Mesh Formation

Following steps, the amount of friction of carbon fibers in non-crimp 3D orthogonal carbon fabric will be defined and at the end quantities and types of elements will be determined. So non-crimp 3D orthogonal carbon fabric is analyzed under tensile force. About 80000 elements have been used and when both tensile and compressive forces are applied, the types of analysis should have been dynamic, explicit and Three-D with C3D4 element under Explicit-3DStress condition and when torsion or flexural torque are implied , C3D10 element under Starndard-3Dstress has been used.

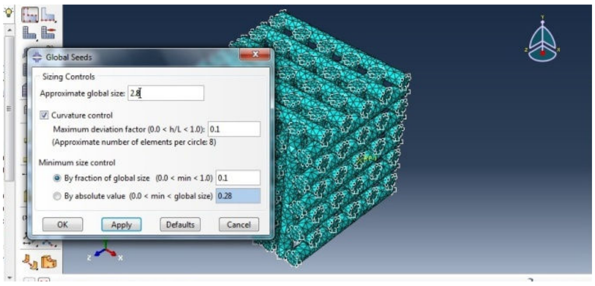
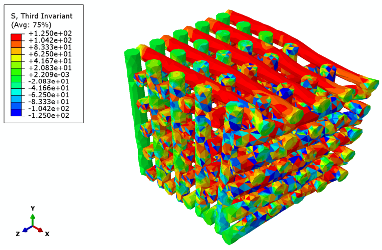


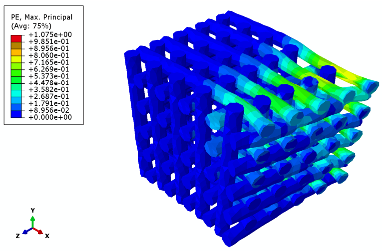
Fig. 5 Mesh generation on non-crimp 3D orthogonal carbon fabric model in ABAQUS

E. Results and Visualizations

Analytical methods and elements which are described in previous steps, have been used to analyze the mechanical behavior of 3D orthogonal carbon fabric in tensile, pressure, flexural and torsional loading. Figs. 6-9 show the cantors of stress and plastic strain of fabric's model under these loading conditions.

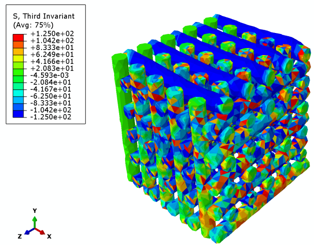


(a)

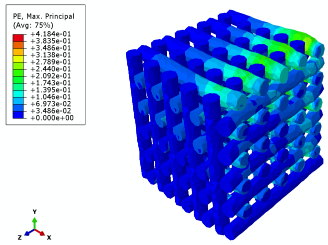


(b)

Fig. 6 Cantors of 3D orthogonal carbon fabric model applied to tensile: (a) Stress, (b) Plastic strain

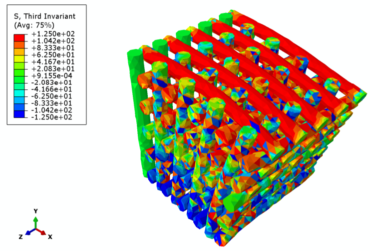


(a)

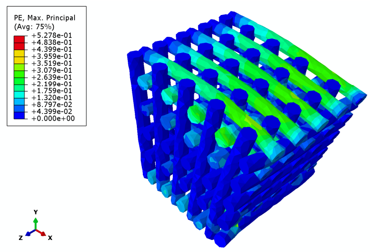


(b)

Fig. 7 Cantors of 3D orthogonal carbon fabric model applied to pressure: (a) Stress, (b) Plastic strain

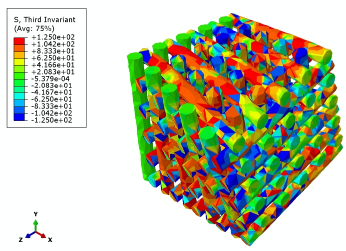


(a)

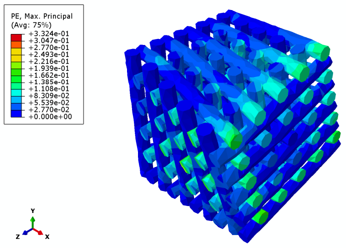


(b)

Fig. 8 Cantors of 3D orthogonal carbon fabric model applied to bending moment: (a) Stress, (b) Plastic strain



(a)



(b)

Fig. 9 Cantors of 3D orthogonal carbon fabric model applied to torsional torque: (a) Stress, (b) Plastic strain

F. Heat Transfer

To analyze the heat transfer in non-crimp 3D orthogonal carbon fabric, Static General Method has been used. In deed in steady state the amounts of heat transfer in non- crimp 3D orthogonal carbon fabric with specified dimension has been evaluated. It should be noted that in heat transfer analysis, thermal conductivity coefficient of carbon is given as an input, while temperature changes and heat flux are determined. To analysis the behavior of non-crimp 3D orthogonal carbon fabric, boundary behavior has been assumed different from mechanical analysis. In this analysis the temperature of bottom of structure is 2000 centigrade degree which is almost equal to 2273 kelvin which has been assumed as boundary conditions. It is shown in Fig. 10 [19]. By importing the amount of heat flux, temperature up to beginning of the structure has been investigated. The type of element in this analysis is DC3D10: 10-node quadratic heat transfer tetrahedron. Fig. 12 is a view of temperature changes alongside of the 3D orthogonal carbon fabric structure. Fig. 12 shows the results of heat transfer of non-crimp 3D orthogonal fabric model.

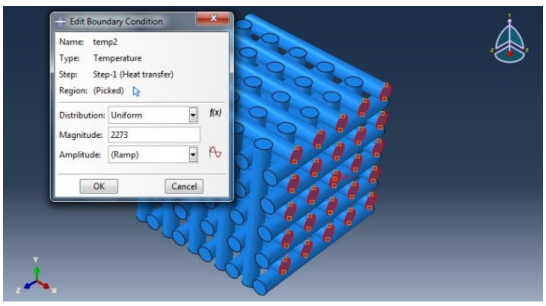


Fig. 10 Boundary condition in heat transfer modeling of non-crimp 3D orthogonal carbon fabric in ABAQUS

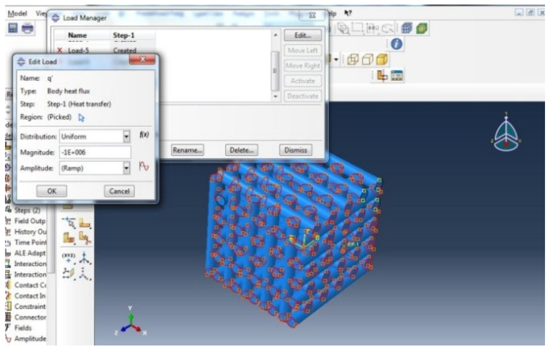
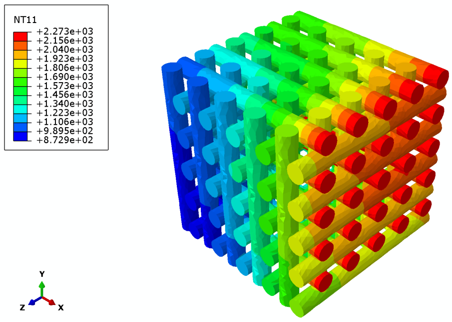
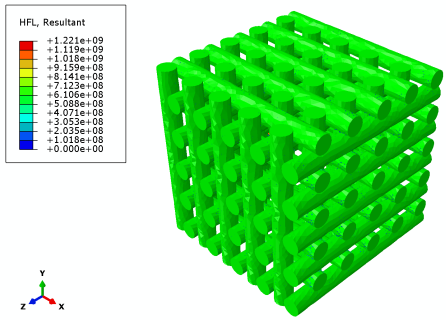


Fig. 11 Heat flux applied to non-crimp 3D orthogonal carbon fabric model in stable condition



(a)



(b)

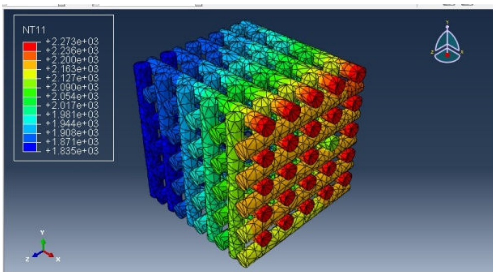
Fig. 12 Heat transfer cantors of 3D orthogonal carbon fabric model in stable condition: (a) Temperature, (b) Heat flux

To analyze the 3D orthogonal carbon fabric with considering the radiant behavior of carbon fiber and also its thermal conductivity, some changes in analysis should be applied. In this kind of analysis, the radiant behavior in determination of contact between surfaces should be defined. In this stage the type of heat transfer between surfaces as a radiant is specified. Also for analyzing 3D orthogonal carbon fabric in this condition, Boltzmann's constant and Kelvin's absolute zero temperature have been used as default [20]. After determining the properties of carbon fiber, including mechanical and thermal (conduction and radiant) and assigning them to 3D orthogonal carbon fabric, boundary conditions should be determined in analysis in which the temperature of bottom of fabric in x-direction has been assumed 2000 centigrade degree or in another word 2273 Kelvin. After that heat flux 10^6 (w/mm^2 ^{o}k) was uniformly applied to 3D orthogonal carbon fabric. The results of analyzing 3D orthogonal carbon fabric is shown in Fig. 13, indicating N11 (Nodal temperature at nodes) or point temperature, HFL (Heat flux vector at integration points) or heat flux at element's node and RFL11 (Reaction fluxes at nodes) or reactions of heat flux at connection nodes of elements.

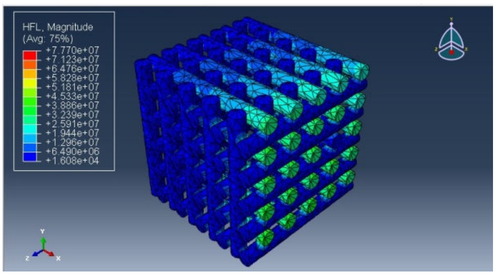
In comparison between a condition in which both radiant and conduction are assumed as heat transmitting factors and a condition where conduction is the mere factor, a sample of structure under this conditions and applying an equal flux and boundary conditions has been analyzed. The results have been compared in Table II. According to the table, with regard to the effect of radiant on thermal transfer, more thermal transition in 3D orthogonal carbon fabric will take place. So for an accurate analysis and close to reality, according to the meaningful effect of radiant on results, it should be considered in analysis.

TABLE II
RESULTS OF HEAT TRANSFER WITH AND WITHOUT RADIATION EFFECT

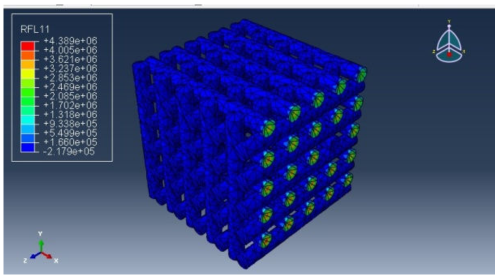
Heat transfer	Nodal temperature at nodes (K)	Temperature difference of carbon fabric in X direction
Conduction	2040-2273	233
Conduction and Radiation	1835-2273	438



(a)



(b)



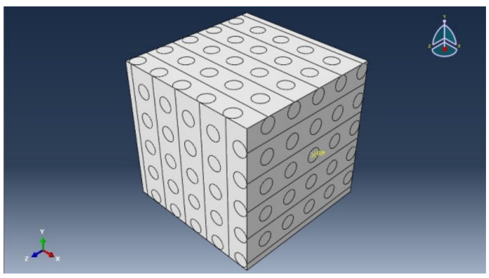
(c)

Fig. 13 Analysis of heat transfer in non-crimp 3D orthogonal carbon fabric model by conduction and radiation: (a) N11 (Nodal temperature at nodes) or point temperature, (b) HFL (Heat flux vector at integration points) or heat flux at element's node, (c) RFL11 (Reaction fluxes at nodes) or reactions of heat flux at connection nodes of elements

V. SIMULATION OF COMPOSITE

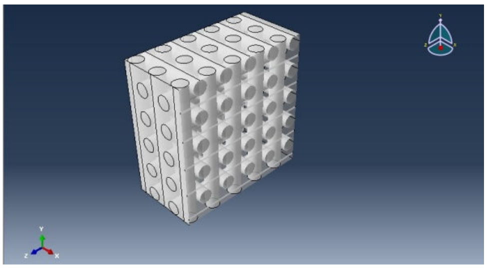
For estimating the behavior of carbon-carbon composite reinforced with 3D orthogonal carbon fabric under different conditions of loading, first of all the geometry of structure should be determined. Dimensions of orthogonal fabric as explained in analysis of 3D orthogonal carbon fabric, is 10*10*10 mm^3 for carbon 12k has been considered and all analysis base on this structure and resin injection into it have been performance. The mechanical properties of 3D orthogonal carbon fabric as explained so far, is assigned to fabric structure. In this stage, as structure is composite, resin should be defined and injects to the structure. So first structure of resin is defined and then its properties will be assigned and resin structure is assembled to 3D orthogonal carbon fabric. Finally Fig. 14 shows a view of composites resulted by injecting carbon resin into 3D orthogonal carbon fabric structure. The middle section of composite was shown in Fig. 14 (b). According to 3D orthogonal carbon fabric structure which has some vacant pores, adding resin will fill these pores.

After determining the geometry and properties of composite, all modules as explained for 3D orthogonal carbon fabric is defined respectively and is assigned to composite. Almost 140000 elements have been assigned to composite structure. Fig. 15 shows schematic of some modules.



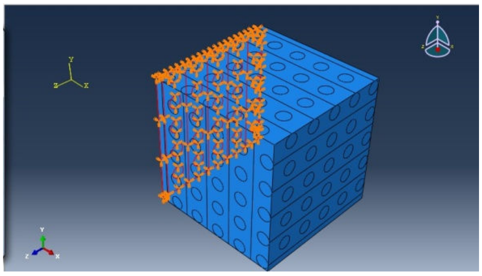
(a)

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:6, 2015

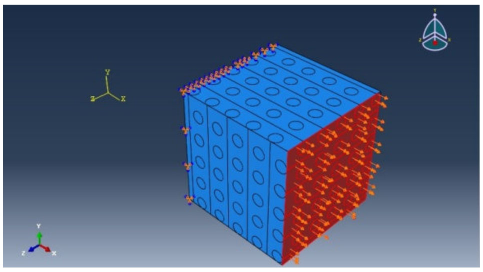


(b)

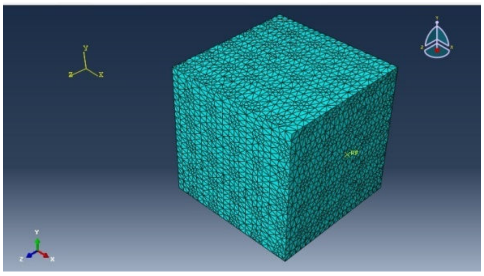
Fig. 14 Simulation of non-crimp 3D orthogonal carbon fabric composite in ABAQUS: (a) Schematic of whole structure, (b) schematic of cross section



(a)



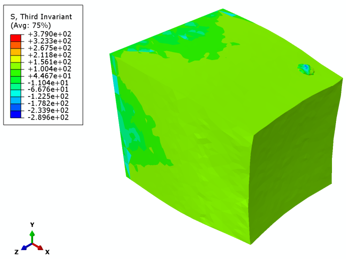
(b)



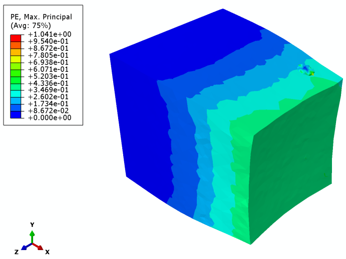
(c)

Fig. 15 Schematics of modules in simulation of non-crimp 3D orthogonal carbon fabric composite in ABAQUS: (a) Boundary conditions, (b) Tensile loading, (c) Mesh generation

Analytical methods and elements which are described in previous steps, have been used to analyze the mechanical behavior of 3D orthogonal carbon composite in tensile, pressure, flexural and torsional loading. Figs. 16-19 show the cantors of stress and plastic strain of composite's model under these loading conditions.

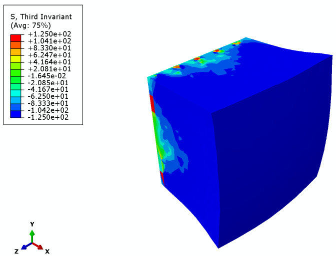


(a)

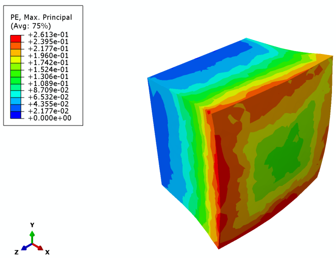


(b)

Fig. 16 Cantors of carbon composite model applied to tensile: (a) Stress, (b) Plastic strain

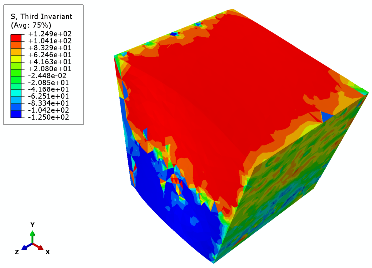


(a)

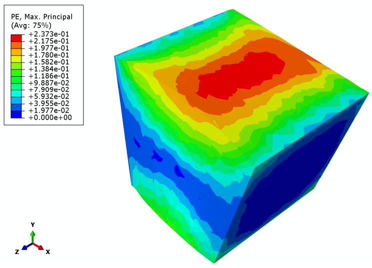


(b)

Fig. 17 Cantors of carbon composite model applied to pressure: (a) Stress, (b) Plastic strain

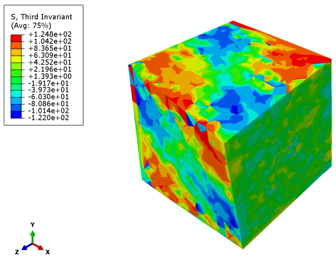


(a)

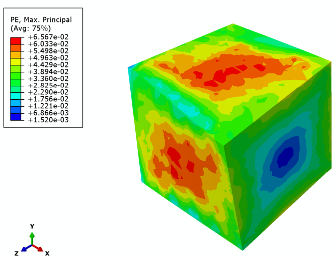


(b)

Fig. 18 Cantors of carbon composite model applied to bending moment: (a) Stress, (b) Plastic strain



(a)



(b)

Fig. 19 Cantors of carbon composite model applied to torsional torque: (a) Stress, (b) Plastic strain

VI. Conclusion

Non-crimp 3D orthogonal carbon fabrics are one of the useful textiles reinforcements in aerospace composites. Since performing mechanical tests on these specific textiles are not economic, studying characteristics of them have been proceeded with simulating in a virtual environment. The mechanical behavior of non-crimp 3D orthogonal carbon fabric composite under different kind of loading as tensile and compressive forces, torsion and flexural torques and thermal transfer has been investigated. The results of mechanical analysis on carbon-carbon orthogonal fabric composites represent that composites structures under pressure will sustain more stresses. While under tensile conditions with the same force and boundary conditions, they sustain less. Also under tensile conditions movement in elements or in other words in whole composite structure are less happened, but the plastic deformation made by applying tensile forces is more than compressive ones. As the composite structure is isotropic, tensile and compressive forces are applied and analyzed only in X-direction and obviously it is extensible for Y and Z-directions. In the case of composites are applied under same quantity of torsion and flexural torques, the structures will sustain more stress under flexural conditions. While structure under torsion conditions with the same quantity sustain less. Also under flexural conditions movements in elements or in other words in whole composite structure occur more often and also the plastic deformation made by applying flexural torques is more than torsion ones.

References

[1] A. C. Long, *Design and Manufacture of Textile Composites*, Woodhead Publishing, 2005, p. 405.
[2] A. P. Mouritz, M. K. Bannisterb, P. J. Falzonb, K. H. Leongb, "Review of Applications for Advanced Three-Dimensional Fibre Textile Composites", *Composites: Part A,* Vol.30, pp.1445–1461, 1999.
[3] A. Miravete, *3-D Textile Reinforcements in Composite Materials*, Woodhead Publishing, 2000, P. 16.
[4] B. Sun, Y. Liu, B. Gu, "A unit cell approach of finite element calculation of ballistic impact damage of 3-D orthogonal woven composite", *Composites: Part B*, Vol. 40, pp. 552-560, 2009.
[5] A.E., Bogdanovich, "Advancements in Manufacturing and Applications of 3-D Woven Preforms and Composites", *Sixteenth International Conference on Composite Materials (ICCM-16)*, Kyoto, Japan, July 8-13, 2007.
[6] P.G., Unal, "3D Woven Fabrics", In: *Woven Fabrics*, Jeon, H.Y., (Ed.), ISBN: 978-953-51-0607-4, InTech-Open Access Publisher, DOI: 10.5772/37492, 2012, p.106.
[7] F., Stig, *3D-woven reinforcement in composites*, PhD thesis, KTH School of Engineering Sciences, Stockholm, Sweden, 2012.
[8] L., Tong, A.P., Mouritz, M.K., Bannister, "*3D Fibre Reinforced Polymer Composites",* Elsevier, ISBN 0-08-043938-1, Netherlands, 2002, p.19-21.
[9] W., Shi, H., Hu, B., Sun, B., Gu, "Energy absorption of 3D orthogonal woven fabric under ballistic penetration of hemispherical-cylindrical projectile", *Journal of The Textile Institute*, Vol. 102, No. 10, pp. 875-889, 2011.
[10] V., Carvelli, J., Pazmino, S.V., Lomov, I., Verpoest, "Deformability of a non-crimp 3D orthogonal weave E-glass composite reinforcement", *Composites Science and Technology*, Vol. 73, pp. 9-18, 2012.
[11] X., Jia, B., Sun, B., Gu, "A numerical simulation on ballistic penetraton damage of 3D orthogonal woven fabric at microstructure level", *International Journal of Damage Mechanics*, Vol. 21, pp. 237-266, 2012.
[12] R., Mishra, J., Militky, B.K., Behera, V., Banthia, "Modelling and simulation of 3D orthogonal fabrics for composite applications", *Journal of the Textile Institute*, Vol. 103, No. 11, pp. 1151-1266, 2012.
[13] M., Karahan, S.V., Lomov, A.E., Bogdanovich, I., Verpoest, "Fatigue tensile behavior of carbon/epoxy composite reinforced with non-crimp 3D orthogonal woven fabric", Composites *Science and Technology*, Vol. 71, pp. 1961-1972, 2011.
[14] S.V., Lomove, A.E., Bogdanovich, D.S., Ivanov, K., Hamada, T., Kurashiki, M., Zako, M., Karahan, I., Verpoest, "Finite element modeling of progressive damage in non-crimp 3D orthogonal weave and

plain weave E-glass composites", *2nd World Conference on 3D Fabrics*, Greenville, South Carolina, USA, 2009.

[15] Ch.,El Hage, R., Younes, Z., Aboura, M.L., Benzeggagh, M., Zoaeter, "Analytical and numerical modeling of mechanical properties of orthogonal 3D CFRP", *Composites Science and Technology*, Vol. 69, pp. 111-116, 2009.

[16] K.J., Bathe, *Finite Element Procedures in engineering Analysis*, Prentice hall, Englewood Cliff, 1996, p. 3-10.

[17] F. L., Stasa, *Applied Finite Element Analysis for Engineers*, Holt, Rinehart and Winston, 1985, p. 11-15.

[18] ww.toraycfa.com/pdfs/T300DataSheet.pdf

[19] J. P., Holman, *Heat Transfer*, 9th Ed, McGraw Hill, 2002.

[20] C. W., Ohlhorst, L., Wallace, O., Philip, *thermal conductivity database of various structural carbon-carbon composite material* , Nasa technical memorandum, 1997.