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Investigation on Flexural Behavior of Non-Crimp 3D Orthogonal Weave Carbon Composite Reinforcement

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Abstract**—**Non-crimp three-dimensional (3D) orthogonal carbon fabrics are one of the useful textiles reinforcements in composites. In this paper, flexural and bending properties of a carbon non-crimp 3D orthogonal woven reinforcement are experimentally investigated. The present study is focused on the understanding and measurement of the main bending parameters including flexural stress, strain, and modulus. For this purpose, the three-point bending test method is used and the load-displacement curves are analyzed. The influence of some weave's parameters such as yarn type, geometry of structure, and fiber volume fraction on bending behavior of non-crimp 3D orthogonal carbon fabric is investigated. The obtained results also represent a dataset for the simulation of flexural behavior of non-crimp 3D orthogonal weave carbon composite reinforcement.

Keywords**—**Non-crimp 3D orthogonal weave, carbon composite reinforcement, flexural behavior, three-point bending.

I. Introduction

FIBER-REINFORCED composite materials have many advantages and are frequently used in a wide variety of applications. 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 3D fiber architectures [1].

Several types of 3D fabrics have been developed and have provided unique characteristics. Among them, the orthogonal fabric composite provides fiber architecture aimed at retaining in-plane performance while increasing interlaminar toughness, by introducing only a small amount of through-thickness (z) reinforcements. 3D orthogonal woven composites have been widely applied to structure engineering due to the high stiffness and strength along both the in-plane and thickness directions. Non-crimp 3D orthogonal woven fabrics have higher Young’s modulus compared with other 3D textiles regarding non-crimp structure. In particular, 3D orthogonal woven composite is more competitive compared to laminated composites and other 3D textile structural composites due to its higher stiffness and strength in three orthogonal directions. Additionally, the 3D orthogonal woven composite allows tailoring the textile properties required for a specific application which could potentially result in a better delamination resistance and damage tolerance, especially in thickness direction [2], [3].

Research studies on mechanical properties of non-crimp 3D orthogonal fabrics are very limited and most of them focus on composites reinforced with this fabric. Analysis of the mechanical behavior of reinforcement serves to understand its behavior and performance in composite manufacturing process and technical application. This paper discusses the flexural behavior of non-crimp 3D orthogonal weave carbon composite reinforcement. 3D orthogonal carbon samples with different structure parameters are subjected to three-point bending test, and flexural properties are obtained. Also, the influence of yarn and structure parameters on bending behavior of non-crimp 3D orthogonal carbon fabrics is investigated.

II. Non-Crimp 3D Orthogonal Fabrics

A non-crimp fabric is a textile such that all warp- and fill-directional yarns remain practically straight in structure. 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.

Non-crimp 3D orthogonal fabric was named NOOBed fabric by Khokar [6]. This name is an acronym for Non-interlacing, Orthogonally Orientating and Binding. These fabrics have three different yarns in three coordinates (x, y, and z) that are not interlaced with each other as in the conventional weaving. Noobing is a non-woven 3D fabric-forming process which assembles three mutually perpendicular sets of yarns with no interlacing (as with weaving), interlooping (as with knitting), or intertwining (as with braiding). Fig. 1 represents non-crimp 3D orthogonal fabric's structure. Orthogonal fabrics can be categorized in two groups; namely uniaxial and multiaxial. The uniaxial noobing process produces uniaxial noobed fabric using three sets of yarns. The multiaxial noobing process produces multiaxial noobed fabric using, typically, five sets of yarns. Fig. 2 shows the fundamental arrangement of yarns in these two noobed fabric types. Using a non-crimp 3D structure as composite reinforcement is obviously beneficial regarding its higher in-plane stiffness and strength [4]-[6].

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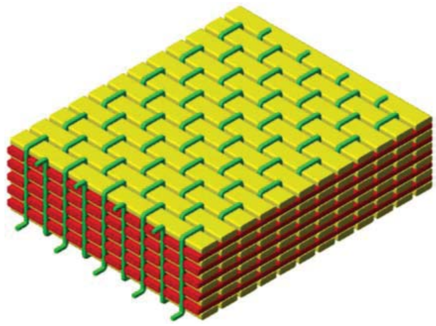

Fig. 1 schematic of non-crimp 3D orthogonal weave [7]

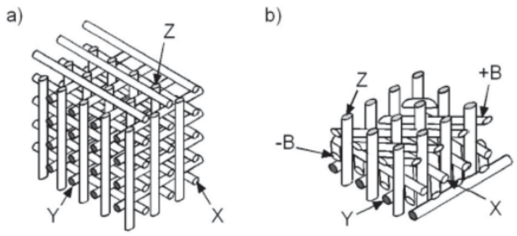

Fig. 2 A noobed structure: (a) uniaxial and (b) multiaxial [6]

Since the 1970's a wide range of processes has been developed to produce 3D orthogonal preforms which include techniques for utilizing relatively conventional weaving mechanisms but with multiple weft insertion, and processes completely different from traditional weaving process. Significant development of machinery to manufacture 3D non-woven preforms 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). Fig. 3 shows some methods for the production of uniaxial non-crimp 3D orthogonal preforms which have been developed by researchers [8].

Shi et al. [9] have presented an analytical model to calculate the energy absorption of the three non-crimp 3D orthogonal fabrics under the ballistic penetration of a hemispherical-cylindrical rigid projectile. They have mentioned that the non-crimp features of warp and weft yarns impart the highest energy absorptions to 3D orthogonal woven fabric with respect to the other kinds of 3D woven fabrics under ballistic impact.

Carvelli et al. [10] have experimentally investigated deformability of a single-ply E-glass non-crimp 3D orthogonal woven reinforcement. 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.

The ballistic impact damages on 3D orthogonal woven fabric penetrated under a conically cylindrical rigid projectile were investigated through experimental analysis and finite-element simulations by Jia et al. [11]. Briefly, Jia et al. constructed a microstructure model of the non-crimp 3D orthogonal fabric by importing the geometry into a finite-element geometrical preprocessor.

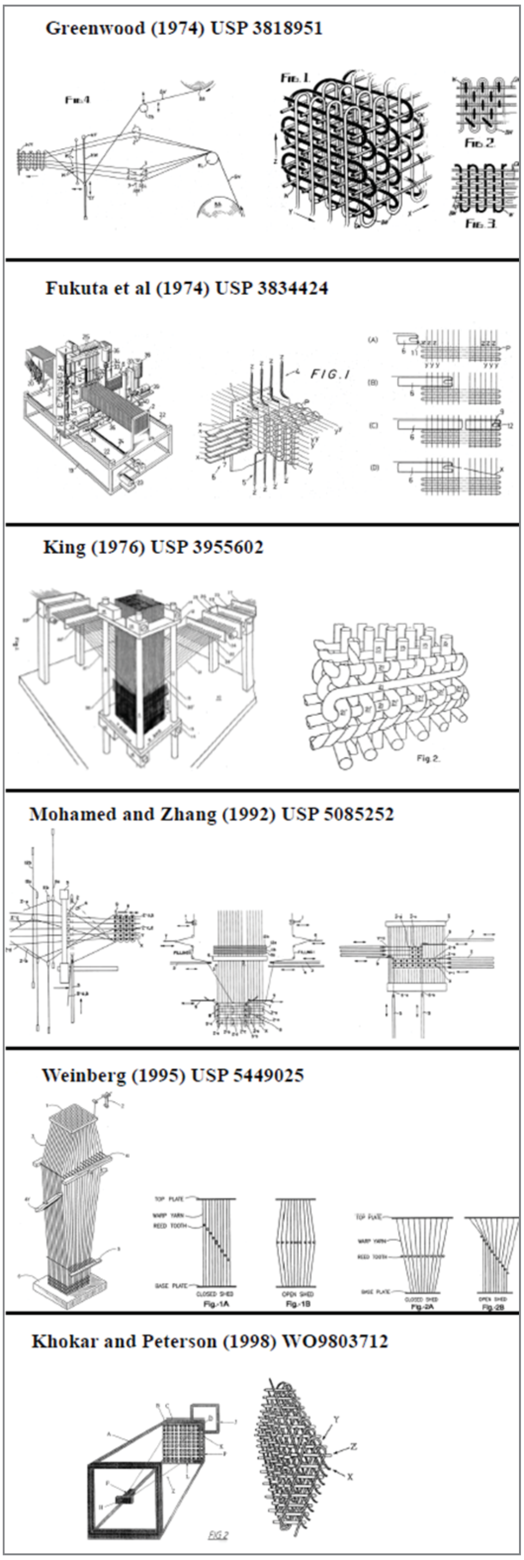

Fig. 3 Illustration of some equipment and methods for manufacturing of 3D non-crimp 3D orthogonal weave [6]

Mishra et al. [2] have focused on geometrical and micromechanical modeling of 3D orthogonal fabrics for composite applications by performing meso-finite element analysis on a unit cell instead of full fabric in ANSYS.

Research and modeling of the mechanical properties of composite reinforced with non-crimp 3D orthogonal fabric were often analyzed by investigating failure mechanisms and damage. Analytical and finite element models to predict the mechanical properties and fracture resistance of these composites were presented [12]-[14].

III. Experimental

A. Materials

The non-crimp 3D orthogonal weave carbon composite reinforcement samples were woven on a self-designed loom in Isfahan University of technology. Carbon filament tows manufactured by Torayca, America Inc., were used for weaving. To determine the influence of yarn type and yarns insertion density in structure of non-crimp 3D orthogonal weave on flexural properties, two types of carbon yarn and tow warp and weft insertion density were chosen. Table I and II list the specifications of carbon fibers and the non-crimp 3D orthogonal weave carbon samples, respectively.

Fig. 4 schematically shows the variety of warp and weft insertion in samples. In A and E samples, there are 10-layer warp and weft yarns in 10 cm of sample, while in B and F samples, there are 20-layer warp and weft yarns in the same sample length.

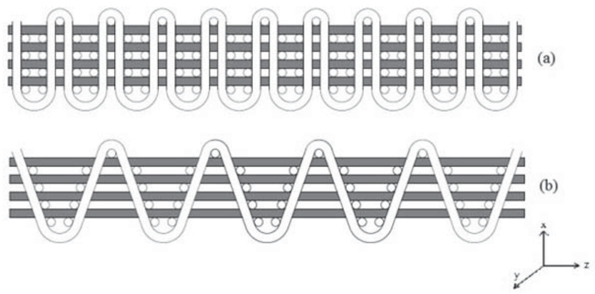

Fig. 4 Schematic of warp and weft insertion variety in non-crimp 3D orthogonal weave samples: (a) 20 layers in 10 cm sample length and (b) 10 layers in 10 cm sample length

TABLE I
PROPERTIES OF CARBON FIBERS

Fiber Type	Number of Filaments	Tensile Modulus *(10^9 N/M^2)*	Elongation *(%)*	Density *(g/cm^3)*	Yield *(g/1000m)*
T300	6000	230	1.5	1.76	400
T300	12000	230	1.5	1.76	800

Fig. 5 shows the photographs of 3D orthogonal weave carbon composite reinforcement samples, in which a comparison of the yarn type and warp and weft yarns insertion density is clearly seen.

Fig. 5 Non-crimp 3D orthogonal weave samples

TABLE II
SPECIFICATION OF NON-CRIMP 3D ORTHOGONAL CARBON SAMPLES

Sample Code		Linear Density *(Tex)*	Insertion Density *(ends/ cm)*	Layers *(/cm)*
	Warp	400	8	1
A	Weft	400	8	1
	Z-yarn	400	16	8
	Warp	400	16	2
B	Weft	400	16	2
	Z-yarn	400	16	8
	Warp	800	8	1
E	Weft	800	8	1
	Z-yarn	800	16	8
	Warp	800	16	2
F	Weft	800	16	2
	Z-yarn	800	16	8

B. Three-Point Bending Test

The three-point bending tests were conducted with Zwick universal testing machine (Type: 144660). Fig. 6 shows the load configuration for a beam in three-point bending test.

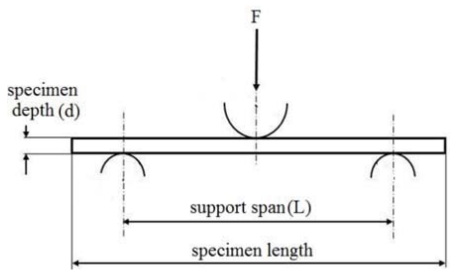

Fig. 6 Load configuration for a beam in three-point bending

The dimensions and all the procedures of the three-point bending test were in accordance with standard ASTM D 7246M [15]. Support length was set 8 cm, and specimen length, support-to-depth ratios, and the applied velocity of the bending load were chosen 10 cm, 16:1, and 2 mm/min, respectively. The maximum of displacement was set 15 mm for all samples. Three specimens of each type of sample were tested and load–displacement plots were obtained for each test specimen.

Fig. 7 A non-crimp 3D orthogonal carbon specimen subjected to three-point bending test

IV. Results and Discussion

This section describes the experimental results after the various non-crimp 3D orthogonal weave samples were subjected to three-point bending. All results were plotted in terms of applied load versus center displacement of the sample under the crosshead of the tester machine. All the samples had the same span length, thus making it possible to superimpose the load/displacement plots for each group of samples. This allowed a more accurate comparison of the resulting curves.

According to ASTM D7246M, flexural stress, strain, and modulus are given by:

$$S = \frac{3PL}{2bd^2} \tag{1}$$

$$r = \frac{6Dd}{L^2} \tag{2}$$

$$E_B = \frac{L^3 m}{4bd^3} \tag{3}$$

where: S is the flexural stress (MPa); P is the load (N); L is the support span (mm); d is the depth of the specimen (mm); b is the width of the specimen (mm); r is the flexural strain (mm/mm); D is the displacement of the center (mm); E_B is flexural modulus (MPa); m is the slope of the tangent to the initial straight-line portion of the load-displacement curve (N/mm).

Figs. 8-11 illustrate the load-displacement and flexural stress-strain plots for A, B, E and F samples. Table Ш shows the dimensions, fiber volume fraction and flexural modulus for each specimen.

TABLE Ш
Measured and Obtained Properties of Non-crimp 3D Orthogonal Carbon Samples

Sample Code	Specimen Depth *(mm)*	Specimen Width *(mm)*	Specimen Length *(mm)*	Fiber Volume Friction *(%)*	E_B *(MPa)*
A	5.55(0.05)	5.56(0.2)	100	50.29(2.11)	54.97(3.68)
B	5.98(0.04)	6.09(0.08)	100	56.2(1.41)	130.29(10)
E	6.21 (0.18)	6.2(0.05)	100	61.74(4.1)	35.39(1.55)
F	7.13(0.04)	7.12(0.03)	100	64.23(0.98)	57.45(3.76)

* *Numbers in parentheses show standard deviation.*

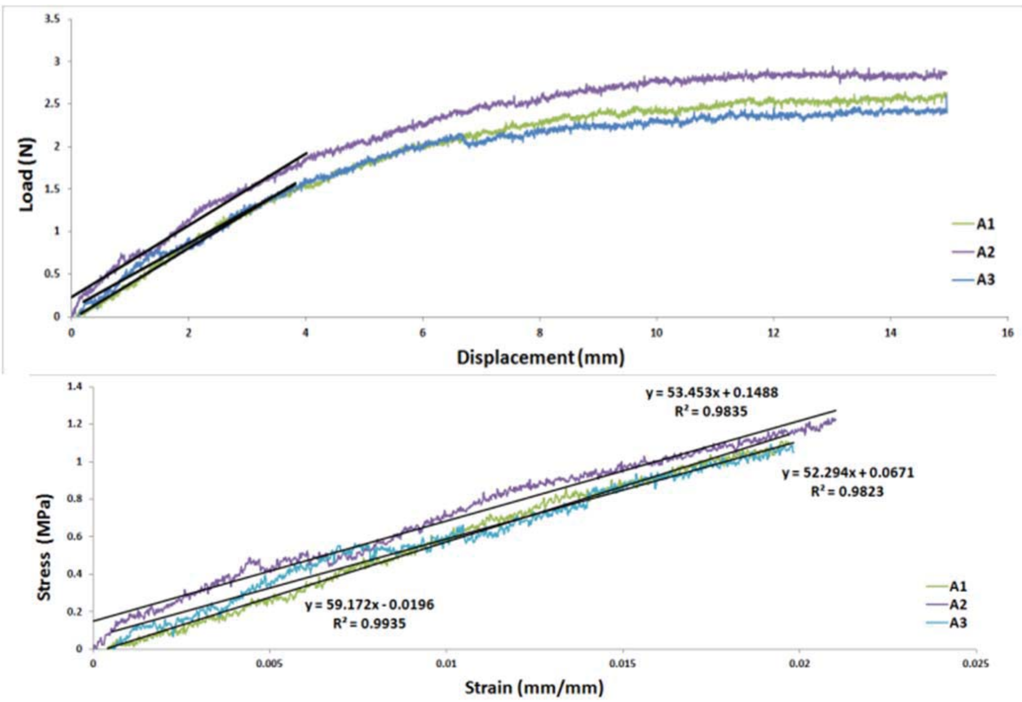

Fig. 8 Load-displacement and flexural stress-strain plots for A sample

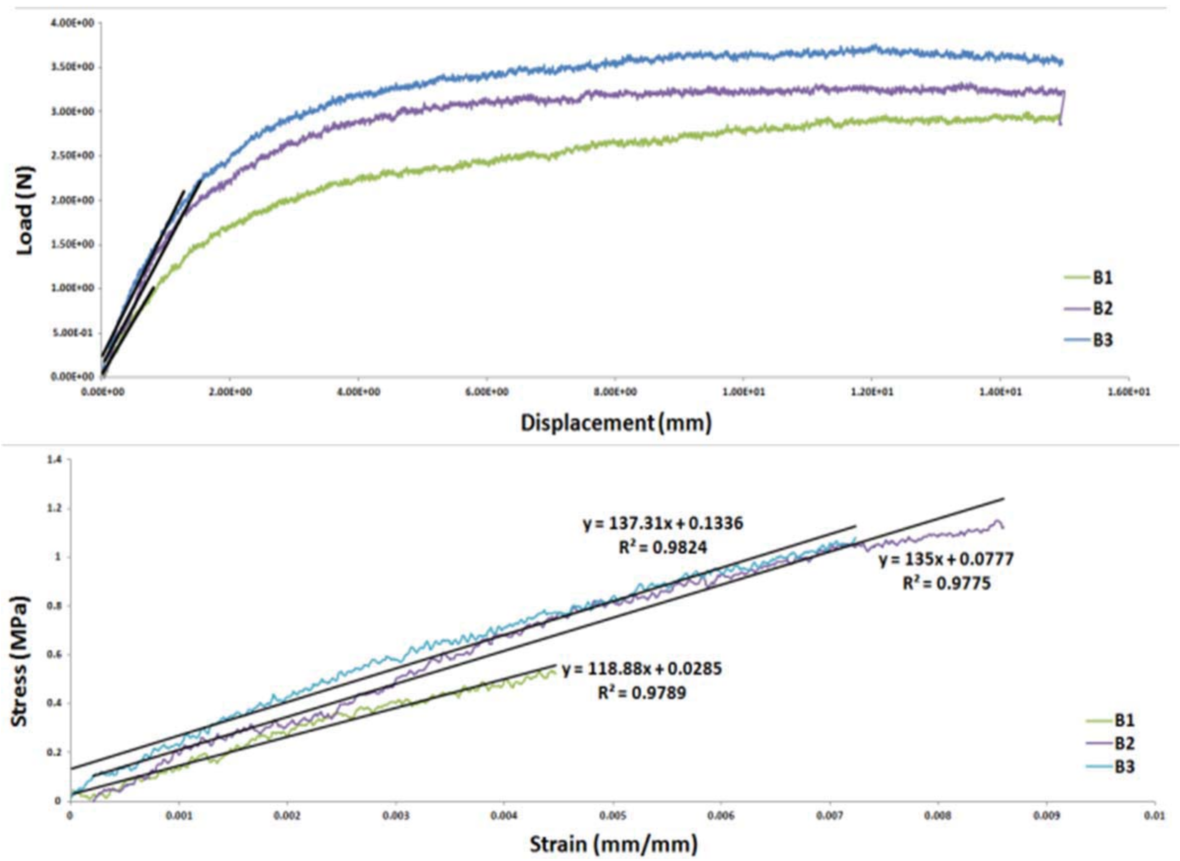

Fig. 9 Load-displacement and flexural stress-strain plots for B sample

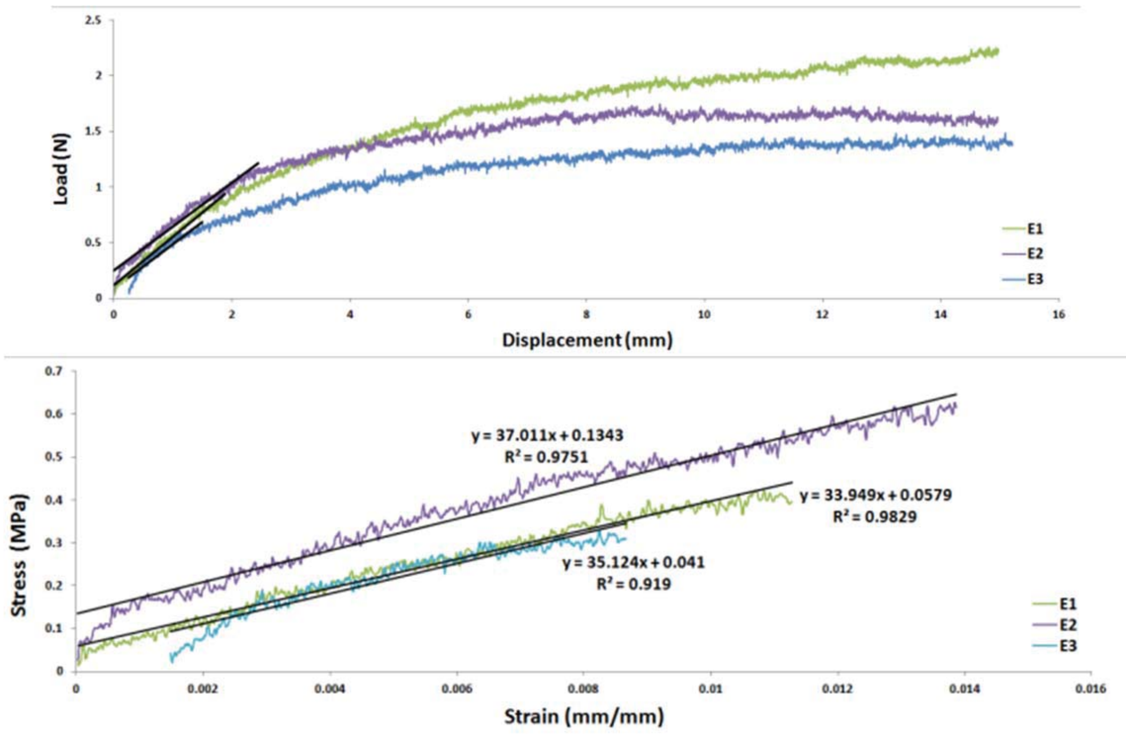

Fig. 10 Load-displacement and flexural stress-strain plots for E sample

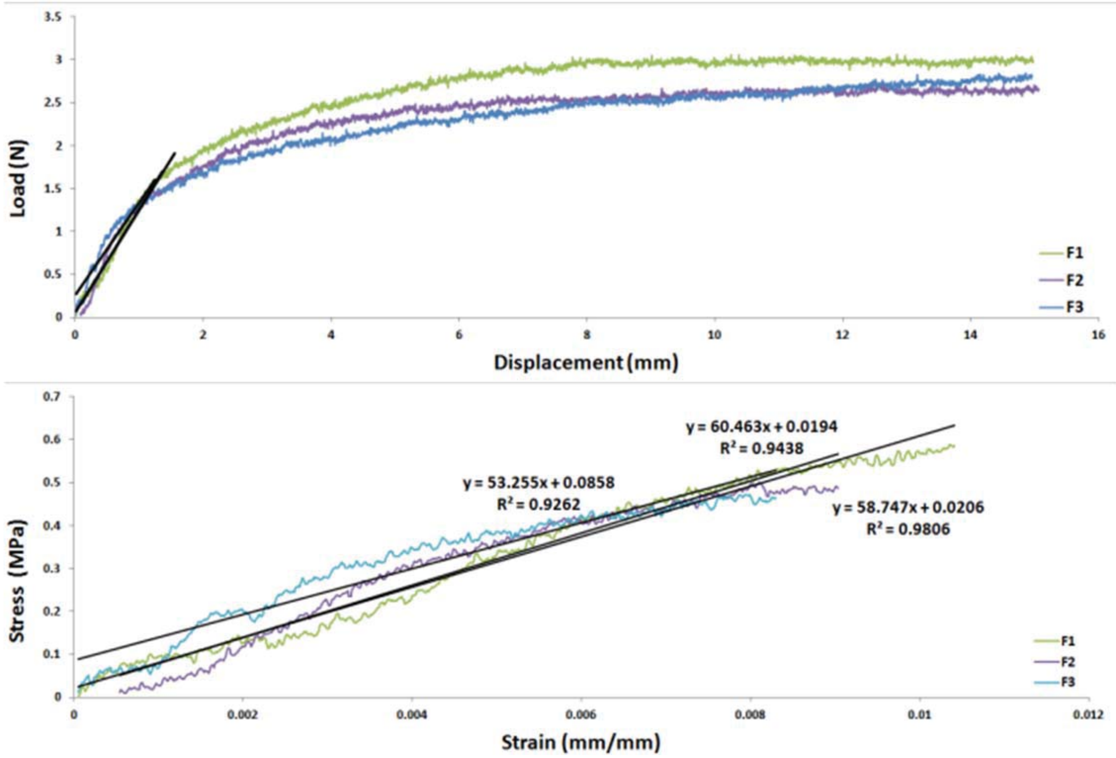

Fig. 11 Load-displacement and flexural stress-strain plots for F sample

The slope of the tangent to the initial straight-line portion flexural stress-strain curve is equal modulus of elasticity in bending (flexural modulus). In each case, there is very good correlation in the flexural modulus results obtained by the formula and curves.

A. Effect of Yarn Insertion Density

Understanding the influence of yarn insertion density of non-crimp 3D orthogonal weave on bending properties is possible by investigating the compression results. As previously mentioned, in A and E samples, the weft and warp yarn insertion density is half of the amount for B and F samples. The weft and warp yarn insertion density increase leads to fiber volume fraction and flexural modulus increase. The flexural modulus of non-crimp 3D orthogonal fabric increases significantly because of increasing the number of cross section yarns participate in bending. It is shown in Fig. 12.

B. Effect of Yarn Type

With increasing number of filaments in carbon fiber, fiber volume fraction of non-crimp 3D orthogonal structure increases, but flexural modulus decreases. It is due to the difference between flexural rigidities of two different yarns; according to the yarn bending test that was done in this research, 6K carbon yarn's flexural length is double of its amount for 12K carbon yarn. So, the flexural rigidity of non-crimp 3D orthogonal weave depends on sizing of yarn's and therefore yarn's flexural rigidity.

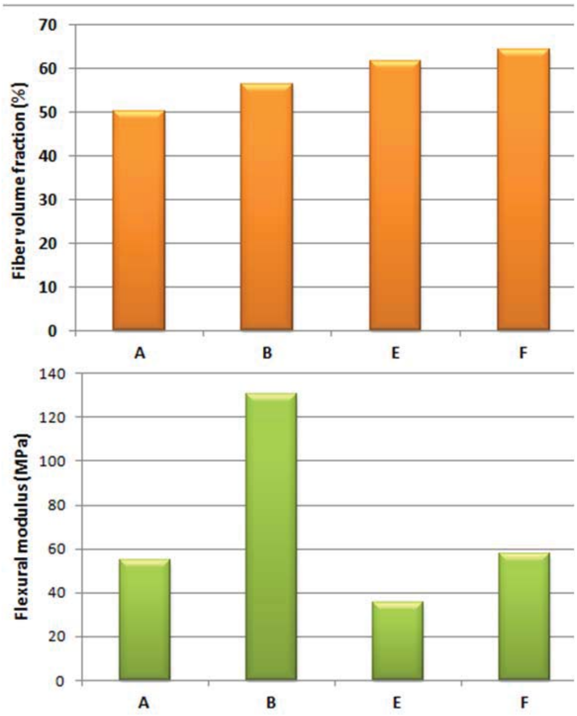

Fig. 12 Fiber volume fraction and flexural modulus of samples

V. Conclusion

Non-crimp 3D orthogonal fabric composite is one of the textile-based composite materials that are rapidly developing in light-weight engineering materials. Analysis of the mechanical behavior of this reinforcement provides information about its performance in composite manufacturing process and technical application. In this paper, the flexural behavior of non-crimp 3D orthogonal weave carbon composite reinforcement was investigated. 3D orthogonal carbon samples with different structure parameters are subjected to three-point bending test, and then the flexural properties were obtained. Also, the influence of yarn and structure parameters on bending behavior of non-crimp 3D orthogonal carbon fabric was discussed. The results show that the increase in the weft and warp yarn insertion density leads to the fiber volume fraction and flexural modulus increase. However, increasing the number of filaments of yarn does not lead to the increase in the flexural modulus presently, and the flexural rigidity of non-crimp 3D orthogonal weave depends on the size of yarns and therefore yarn's flexural rigidity.

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